OsloMet – Oslo Metropolitan University

Department of Civil Engineering & Energy Technology

Section of Civil Engineering

Master Program in Structural Engineering & Building Technology

MASTER THESIS

TITLE OF REPORT	DATE
Reducing global warming impact for Kjøkøysund based on alternative bridge designs	24-05-2022
	PAGES / ATTACHMENTS
	129 / 17
AUTHOR(S)	SUPERVISOR(S)
Besian Kadri	Gro Merkeset
Muhammad Nazar Syahrul	Torbjørn Valnes

IN COLLABORATION WITH	CONTACT PERSON
OsloMet- Oslo Metropolitan University	Dimitrios Kraniotis

SUMMARY / SYNOPSIS

Concrete manufacturing account for almost one tenth of the global CO_2- emissions. A big portion of the concrete greenhouse gas emission comes from the production of cement, still concrete is the most used construction material in the world. New types of concrete have been and are under development in order to reduce their global warming impact. One of the new concrete types is low carbon concretes. These types of concrete have been utilized widely in the building industry but is absent in larger bridge constructions.

The main goal for this thesis is to investigate the possibilities for material and design change of Kjøkøysund bridge, with the goal to reduce the global warming impact. Kjøkøysund bridge is a concrete cantilever bridge, which connects Kråkerøy and Kjøkøy. There has been done a condition assessment on the bridge, and the conclusion of this work is to tear the existing bridge and construct a new one next to it. The report from Statens Vegvesen "Bærekraftige betongkonstruksjoner" has been used to investigate the possibilities to optimize and reduce the greenhouse gas emissions for concrete bridges. Some of the possible solutions in the report is to change materials or superstructure design.

In this thesis the research question has been approached by conducting a literature study. The gathered information has been employed on the case study '' Material and design change on Kjøkøysund bridge''. Various designs with different materials and superstructures have been investigated for an alternative solution for Kjøkøysund bridge. EPD from different concrete and steel supplier have been collected and used in a calculation to find most environmentally friendly material. For the transportation stage A4, the transport calculator provided by Østfoldforskning have been used. To verify these results a life cycle assessment with the software One Click LCA have been conducted, with several other bridge designs which was considered to be suitable for Kjøkøysund bridge.

Regarding global warming impact for Kjøkøysund bridge, alternative bridge solutions have been presented in this thesis. Since this thesis have a broad approach and not focused on one specific solutions, further research must be conducted.

KEYWORDS
Kjøkøysund bridge
Alternative material and design
Life cycle assessment

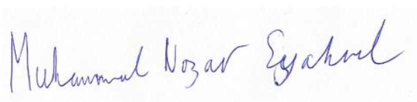
Preface

This thesis is written as a conclusion to a 2-year master's degree in civil engineering at OsloMet Metropolitan University. The thesis was written in the spring of 2022 in collaboration with OsloMet. It corresponds to 30 study credits.

Before the last semester, we were at a seminar organized by OsloMet. Presentations of several different themes from different professors were held here. In that seminar we got to hear about low carbon concrete from Gro Markeset, which sparked an interest in both of us. Therefore, it was natural for us to contact Gro to hear more about this, and later chose to write about this theme.

We would like to thank our supervisors at OsloMet and SWECO, Gro Markeset and Thorbjørn Valnes, for the follow-up and input during the writing and implementation of the assignment.writing and completing of this thesis.

OsloMet 24. May. 2022



Besian Kadri

Muhammad Nazar Syahrul

Abstract

Concrete manufacturing account for almost one tenth of the global CO_2- emissions. A big portion of the concrete greenhouse gas emission comes from the production of cement, still concrete is the most used construction material in the world. New types of concrete have been and are under development in order to reduce their global warming impact. One of the new concrete types is low carbon concretes. These types of concrete have been utilized widely in the building industry but is absent in larger bridge constructions.

The main goal for this thesis is to investigate the possibilities for material and design change of Kjøkøysund bridge, with the goal to reduce the global warming impact. Kjøkøysund bridge is a concrete cantilever bridge, which connects Kråkerøy and Kjøkøy. There has been done a condition assessment on the bridge, and the conclusion of this work is to tear the existing bridge and construct a new one next to it. The report from Statens Vegvesen "Bærekraftige betongkonstruksjoner" has been used to investigate the possibilities to optimize and reduce the greenhouse gas emissions for concrete bridges. Some of the possible solutions in the report is to change materials or superstructure design.

In this thesis the research question has been approached by conducting a literature study. The gathered information has been employed on the case study '' Material and design change on Kjøkøysund bridge''. Various designs with different materials and superstructures have been investigated for an alternative solution for Kjøkøysund bridge. EPD from different concrete and steel supplier have been collected and used in a calculation to find most environmentally friendly material. For the transportation stage A4, the transport calculator provided by Østfoldforskning have been used. To verify these results a life cycle assessment with the software One Click LCA have been conducted, with several other bridge designs which was considered to be suitable for Kjøkøysund bridge.

Regarding global warming impact for Kjøkøysund bridge, alternative bridge solutions have been presented in this thesis. Since this thesis have a broad approach and not focused on one specific solutions, further research must be conducted.

Table of contents

Figure list

Table list

List of acronyms

Acronyms	Full Name
LCA	Life cycle assessment
EPD	Environmental product decleration
GWP	Global warming potential
GHG	Greenhouse gases
NS	Norsk Standard
SVV	Statens vegvesen
EU	European union
HRC	Hot rolled coil
WR	Wire rod
EAF	Electric arc furnace
DRI	Direct reduced iron
UHPC	Ultra-high-performance concrete
HPC	High performance concrete
CED	Cumulative energy demand
ODP	Ozone depletion potential
HP	Human toxicity
POFP	Photochemical oxidant formation
PMF	Particulate matter formation
HSS	High-strength steel
ADP	Abiotic depletion potential
NB37	Norsk Betongforening publication 37
Eqv	Equivalent
LCI	Life cycle inventory

1. Introduction

Human societies rely on concrete structures to be able to live a modern life. On the other hand, they produce a large contribution to greenhouse gas emissions, which is a major cause of climate change. This is primarily due to cement's embodied environmental impact, which accounts for about one tenth of worldwide CO_2 -emissions. Material development is continually being investigated in order to reduce harmful emissions. Construction materials account for a large portion of a construction project's overall CO_2 emissions. Diesel fuel is used in the transportation of batched concrete as well as on-site installation activities such as pumping, vibrating, and finishing concrete. This material is widely used in the making of bridge constructions.

There are many different types of bridges available today. From massive suspension bridges to smaller, simpler beam and plate bridges. Concrete's use and demand as a building material has increased. This development, combined with industrialization, has prompted a desire to improve the efficiency of bridge construction using concrete. Road authorities are responsible for a vast number of aging bridges, many of which fail to satisfy current criteria due to corrosion and other structural flaws, as well as the increasing demands imposed by increased traffic intensity and axle loads. As a result, material choice and design have become extremely important.

1.1 Objectives

The purpose of this master's thesis is to investigate the choice of material for bridge constructions, with a focus on the Kjøkøysund bridge. The Kjøkøysund bridge will be rebuilt, and the thesis looks at various measures that can be taken on design and material selection to reduce greenhouse gas emissions. The goal is to produce a proposal that is more environmentally friendly than what has already been proposed, by discussing different designs and material choices. Several ways of calculating global warming impact have been used, such as LCAs, EPDs and transport calculators.

Low carbon concrete is something that is constantly being researched as a solution to make concrete more environmentally friendly. It has been chosen to look more closely at this material and the possibility of using it on a cantilever bridge. Other bridge construction solutions have been evaluated, to see if they are relevant for the Kjøkøysund bridge based on spans.

1.2 Research questions and methods

With this master's thesis, the main goal is to produce proposals for various measures that can be done to make the Kjøkøysund bridge more environmentally friendly. The research question is therefore as follows:

How will the choice of material and design affect the global warming impact of bridge structures?

To answer the problem, a quantitative method has been used in the form of collecting information from previous literature studies, in order to do a calculation in the case study of the Kjøkøysund bridge.

A literature study can be defined as a comprehensive study and interpretation of existing literature that deals with a specific topic. This thesis is not based on a pure literature study, but extensive work has nevertheless been done to examine sources such as scientific reports and articles. In the case study, calculations were made related to the Kjøkøysund bridge and together with the literature study, a basis is formed for the discussions and the results presented in this thesis.

1.4 Limitations

This thesis will focus on the environmental aspects of concrete structure and alternative designs. Cost analysis and other factors regarding cost will not be considered in this thesis. Since this thesis is a literature study, there will be some simple calculations, but not any capacity control calculations since it is assumed done and controlled in the literature study. In this thesis only bridges which it suited for the Kjøkøysund bridge have been covered. It might be other bridges designs which can meet the requirements for Kjøkøysund, like suspension bridges and cable stay bridges. These bridges are more suited for longer spans and therefore not included in this thesis.

1.5 Organization and structure

The master's thesis has been divided into the following chapters:

- Chapter 1. Introduction
  Description of the thesis' background, purpose, method and limitations.

- Chapter 2-4. Theory
  General theory of greenhouse gas emissions, utility structures and materials
- Chapter 5-6. Theory related to the solution of case study
  Description and comparison of different bridge constructions related to Kjøkøysund bridge.
- Chapter 7. Case study
  Calculation of CO_2 emissions based on proposals for various solutions of the Kjøkøysund bridge
- Chapter 8. Results and discussion
  Discussion of the calculations and measures made in case study
- Chapter 9. Conclusion and further research
  Conclusion and suggestions for future research based on case study presented in this master's thesis

2. Carbon footprint

Climate change is one of the major challenges the global community must overcome in the upcoming years. Carbon footprint is the greenhouse gases which are released by an action or by manufacturing a product [1]. The possibility to measure carbon footprint varies from a single product to an entire country. For construction and structures there are two parts where it is meaningful to calculate the carbon footprint, the embodied carbon and operational carbon [2], the difference is shown in figure 1.

Figure 1: Embodied and operational carbon [2]

When talking about climate changes there are several types of environmental impact such as human health, ozone breakdown, smog etc. The most concern impact is rising temperature which causes extreme weather and rising sea levels [3].

2.1 CO_2- equivalents

Rising temperatures are caused by greenhouse gas emissions which prevent heat from escaping from the atmosphere. This layer also prevents the earth from becoming too cold and freeze over. Naturally this balance is self-regulated, but human caused greenhouse gas emission is disturbing and modifying this system [4]. An example of how GHG emission impacts the environment is shown in figure 2.

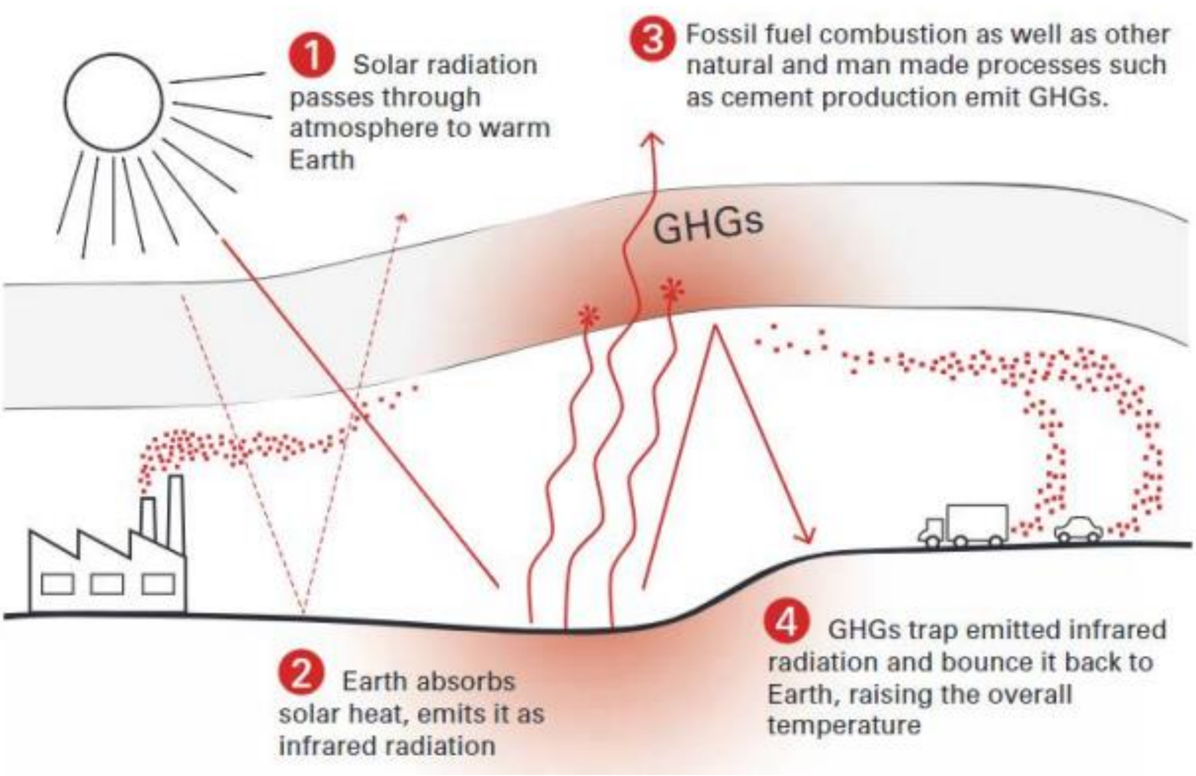


Figure 2: How emissions impact the environment [5]

There are ten primary greenhouse gases. The most common is water vapor (H_2O), carbon dioxide (CO_2), Methane (CH_4) and nitrous oxide (N_2O).

Since the gases have different characteristics, it can be difficult to calculate the carbon footprint based on the emissions. In order to be able to compare the carbon footprint one must look at the gasses global warming potentials (GWP) over a 100- years period. The reference gas which is carbon dioxide, has a GWP of 1 [4]. Table 1 shows the main greenhouse gases and their concentration and global warming potential.

Methane has a GWP of 28, this means methane is 28 times more effective to trap the heat than carbon dioxide over a time period of 100- years. The most destructive gas is Sulphur hexafluoride (SF_6) with a GWP of 23 500.

Table 1: GWP of different gasses [4]

Compound	Pre-industrial concentration (ppmv*)	Concentration in 2019 (ppmv)	Atmospheric lifetime (years)	Main human activity source	GWP**
Carbon dioxide (CO_2)	280	411	variable	Fossil fuels, cement production, land use change	1
Methane (CH_4)	0.715	1.877	12	Fossil fuels, rice paddies, waste dumps, livestock	28
Nitrous oxide (N_2O)	0.27	0.332	121	Fertilizers, combustion industrial processes	265
HFC 23 (CHF_3)	0	0.000024***	222	Electronics, refrigerants	12,400
HFC 134a (CF_3CH_2F)	0	0.000062***	13	Refrigerants	1,300
HFC 152a (CH_3CHF_2)	0	0.0000064***	1.5	Industrial processes	138
Perfluoromethane (CF_4)	0.00004	0.000079***	50,000	Aluminum production	6,630
Perfluoroethane (C_2F_6)	0	0.0000041***	10,000	Aluminum production	11,100
Sulphur hexafluoride (SF_6)	0	0.0000073***	3,200	Electrical insulation	23,500

2.2 LCA- Life cycle assessment

Lice cycle assessment is a method to determine a product's carbon footprint. There are several stages during a product's life where it emits greenhouse gases. Life cycle assessment can be conducted on human activities and material production. Since the material goes through several stages during its lifetime, like raw material extraction, manufacturing, distribution, use and disposal, the manufacturer can analyze where changes can be made in order to reduce the carbon footprint most effectively [6]. A life cycle for a building is shown in figure 3.

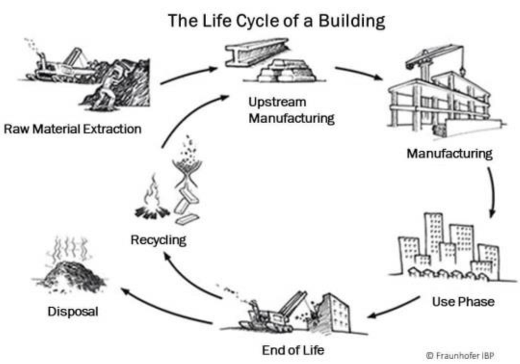


Figure 3: Life cycle of a building [7]

A LCA is built up consists of four steps [8]:

1. *Goal and scope definition:* Define what is the meaning and purpose of the LCA study

2. *Inventory analysis (LCI):* LCI is the most scientific part of the LCA. At this step it is important to know the products' life cycle from cradle to grave. In order to get a good LCI one must enlighten the data collection, data calculation and allocation of flows and releases for the product.

3. *Impact assessment:* This step shows the products' environmental impacts. These impacts are categorized in effect categories such as GWP and water consumption.

4. *Interpretation*: Comments for the analysis, if it has made some assumptions or choices are made that might influence the results.

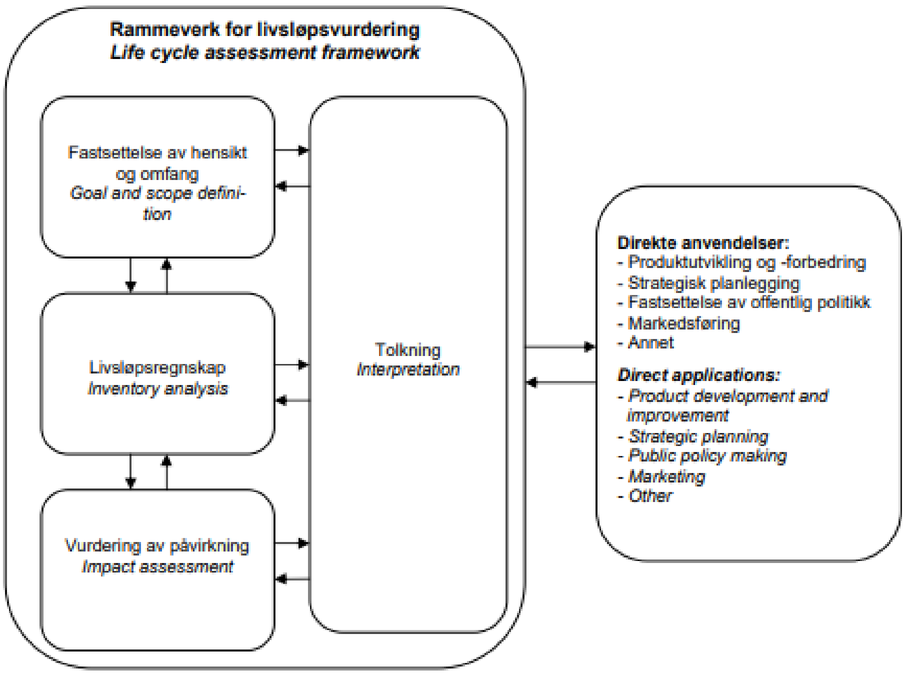


Figure 4: Life cycle assessment framework [7]

According to the European standards EN 15978 and EN 15804, a construction goes through 5 stages during its lifetime, also called system boundary for the product [9].

- A1- A5: Production and construction process stage
- B1- B7: Use and operational stage
- C1- C4: End of life stage
- D: Benefits beyond the system boundary

Table 2: System boundary of a life cycle assessment. Table is made with the information from [9]

Module	Description	Stage	Carbon footprint
Production Stage	Raw material supply	A1	Embodied Carbon
	Transport	A2	
	Manufacturing	A3	
Construction stage	Transport to building site	A4	
	Installation	A5	
Use and operational stage	Use and application	B1	Operational Carbon
	Maintenance	B2	
	Repair	B3	
	Replacement	B4	
	Refurbishment	B5	
	Operational energy use	B6	
	Operational water use	B7	
End- of- life stage	Demolition	C1	
	Transport	C2	
	Waste processing	C3	
	Disposal	C4	
Benefits stage	Reuse	D	
	Recovery	D	
	Recycling	D	

2.2.1 EPD- Environmental Product Declaration

EPD's is a concise summary documents that shows products or services environmental impacts [10]. An EPD is a standardized method to enlighten the environmental profile independent of country for the same product category. The method is created by performing an LCA with the guidelines given in ISO 14040- 14044 [10].

EPD gives a better picture and insight when a decision about which product or system should be chosen based on environmental criteria. Since EPD is standardized, it can also be collected and summarized which then can be used as a foundation for environmental impacts assessment for a whole project. Figure 5 shows the system boundaries and results for an EPD.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage			Construction installation stage		User stage							End of life stage				.	Beyond the system bondaries
Råmat erialer	Transport	Tilvirkning	Transport	Konst ruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskift inger	Renov ering	Operasjonell energibruk	Operasjonell vannbruk	Demon tering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenv inning/ resirkulering- poten siale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	.	MND

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,84E+02	1,69E+00	2,70E+00	1,62E+00
ODP	kg CFC11 -eq	4,39E-06	1,01E-07	4,77E-07	3,07E-07
POCP	kg C_2H_4-eq	2,24E-02	2,69E-04	5,46E-04	2,88E-04
AP	kg SO_2 -eq	4,65E-01	4,63E-03	1,99E-02	5,72E-03
EP	kg PO_4^{3-} -eq	1,58E-01	6,73E-04	4,30E-03	1,19E-03
ADPM	kg Sb -eq	1,10E-04	4,07E-06	3,56E-06	3,59E-06
ADPE	MJ	8,34E+02	2,76E+01	3,86E+01	2,48E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Figure 5: Example of an EPD for a product. For concrete and steel, it is often the system boundaries from A1 to A3 which are included. [11]

3. Bridge

3.1 Bridge construction

Although bridges can be classed in a variety of ways, the most frequent method is to classify them according to their structural shape. This is required since the structural form is the most significant component influencing the bridge's whole service life, including design, building, repair, and maintenance. Bridges of various structural shapes have their own load transfer path and application range. Beam bridges, rigid-frame bridges, truss bridges, arch bridges, cable-stayed bridges, and suspension bridges are some types of bridges [12].

3.1.1 Beam

These types of bridges are the easiest and most common types of bridges. They carry the load vertically from bending forces in the beam and to axial compression forces in the supports. It can be made up of a single span, which is known as a single supported bridge or by several spans, which is known as a continuous supported bridge. Internal forces such as the bending moment and shear force must be resisted by the beam itself in order to resist the weight of the beam and any external loads. When a beam is subjected to a positive bending force, typically above the pillars, the top fibers are compressed, and the bottom fibers are tensioned. This is more complicated than a cable in tension or a compression arch. For this reason, the beam material must be able to handle both tension and compression well [12]. Figure 6 shows the layout of a multi- span beam bridge.

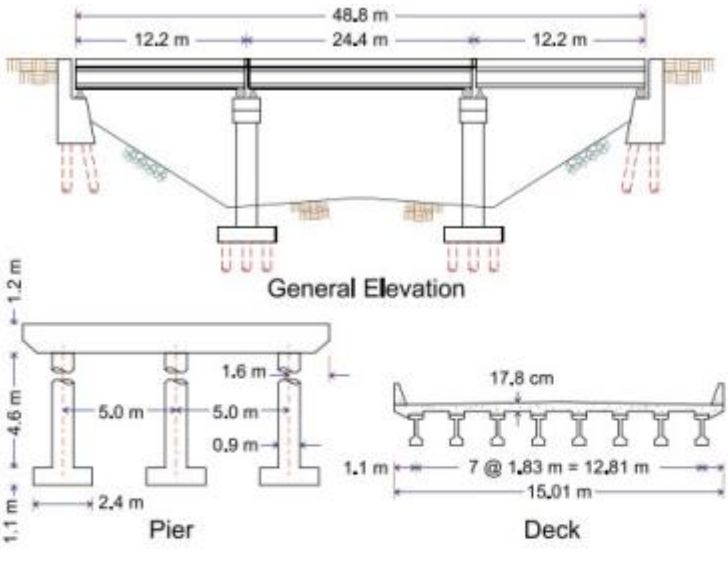


Figure 6: A typical multi span beam bridge [13]

3.1.2 Arch

The main structure of an arch bridge is made up of arches or reinforced arches. If the horizontal reaction force caused by the loading of vertical loads is efficiently applied and they are suitably built to minimize sectional forces of members, arch bridges are cost - effective and advantageous. Arch bridges, which are utilized for long-span bridges after suspension and cable-stayed bridges, have been widely employed around the world due to their unique aesthetics. Arches have different structural qualities depending on their shape and number of hingers. Arches become stronger in general as the number of hinges reduces; nonetheless, this has a significant impact on settlement [14].

Arch bridges carry the load by compression which is transferred to the foundations. The foundations must withstand the compression forces such as vertical compression and horizontally sliding forces. Therefore, arch bridges require good foundation conditions [14]. A typical arch bridge is shown in figure 7.

Figure 7: Arch bridge [14]

3.1.3 Truss

A truss bridge is one whose load-bearing superstructure is made up of connected pieces forming triangle units. Truss bridges are one of the most common modern bridge forms. Trusses are commonly believed to be pinned connections between adjacent truss elements to ease calculations. As a result, truss members such as chords, verticals, and diagonals only act under tension or compression. Short-span truss bridges are usually built as simple supported structures, but long-span truss bridges are usually built as continuous truss bridges or cantilever truss bridges [12] . Figure 8 shows a typical truss bridge.

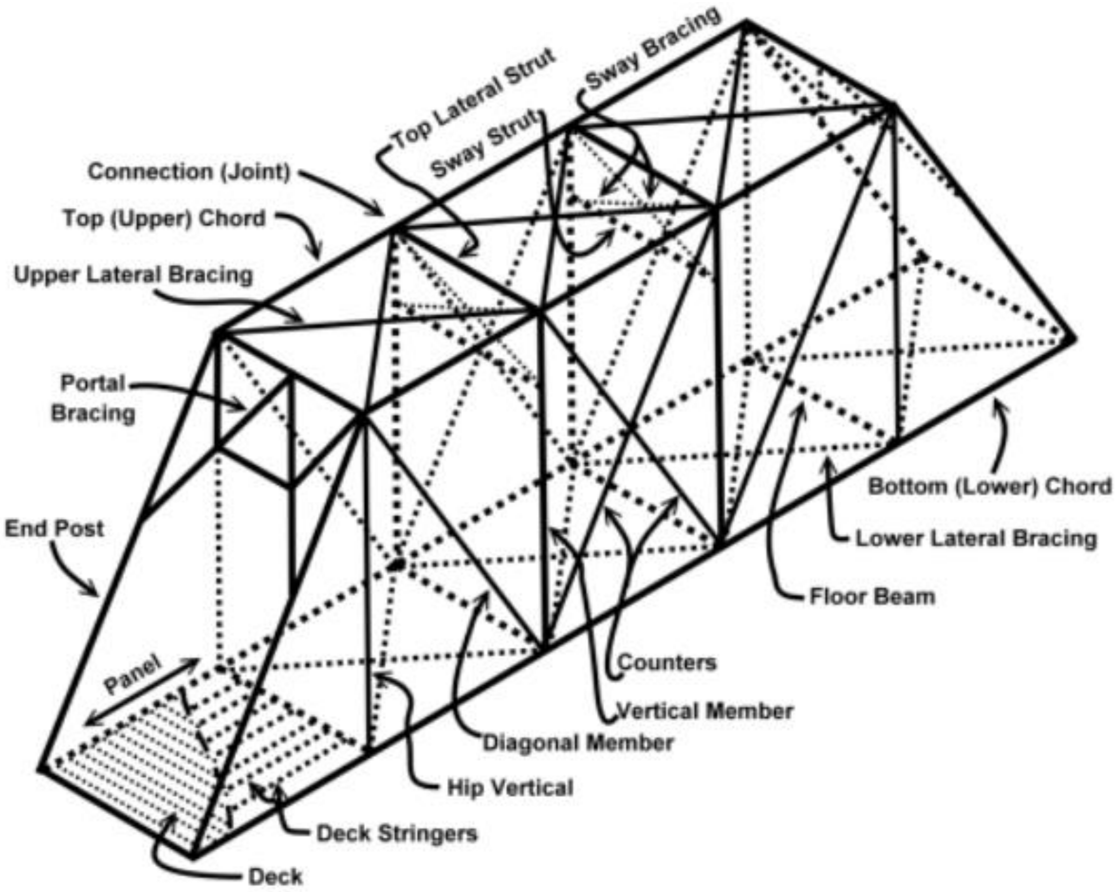


Figure 8: Components of a truss bridge [15]

3.1.4 Suspension

A suspension bridge has a deck that is supported by main cables that are extended across the span from towering towers above the deck. Suspender cables connect the deck to the main cable, allowing it to "hang" from the main wires. Anchorages hold the distant ends of the main cable, known as backstays, in place. Suspension bridges typically have three spans: a center span flanked by "anchor" or "side" spans, all of which are held in place by the suspension system [15]. Since suspension bridge decks lacks torsion support the decks must be built heavy or stiff enough to reduce the movement under loading [15]. Figure 9 shows the layout of suspension bridge.

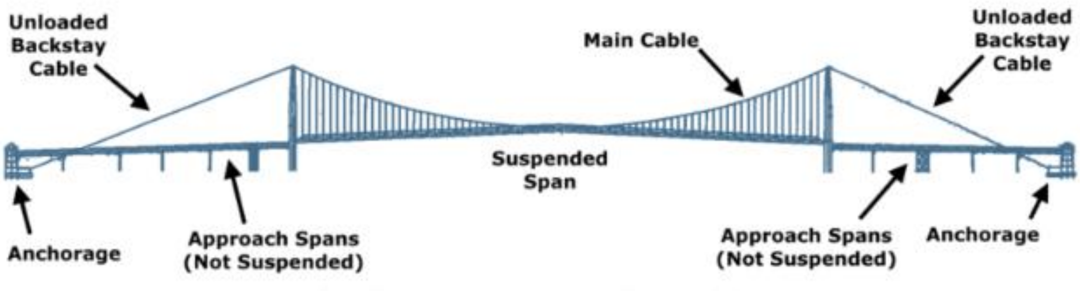


Figure 9: Main components of a suspension bridge [15]

3.1.5 Cable- stay bridge

A cable-stayed bridge has one or more towers, cable-stays, and major girders, with inclined cables supporting several spots in each span upward in a slanting orientation. [12]. Internal forces owing to both dead and live load are fewer in cable-stayed bridges than they are in continuous girder bridges. A cable-stayed bridge is a statically indeterminate continuous girder with spring limitations from a mechanical standpoint. Because its structural components primarily act in tension or compression, cable-stayed bridges are also highly efficient in terms of material utilization [12].

After suspension bridges, cable-stayed bridges have the second-longest spanning capacity and are practicable for spans up to 1000 meters [12]. Figure 10 shows the layout of a cable stayed bridge.

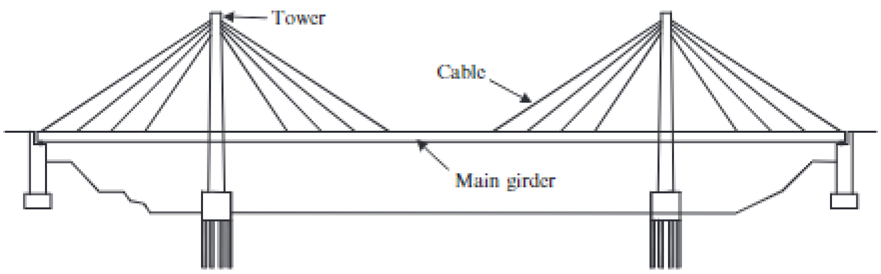


Figure 10: Components of cable- stayed bridge [12]

3.1.6 Cantilever

Cantilever bridges are girder or truss bridges with cantilevers as their primary structural elements. A cantilever bridge provides benefits in both simply supported and continuous bridges, such as being suited for foundations with uneven settlement, being built without false-works, and having a wider span capacity [12]. In cantilever bridges with balanced design, hinges are usually located at contra flexure points of a continuous span, and a simply supported span beam can be suspended between two hinges. Cantilever bridges are commonly employed in truss bridges as well as girder bridges [12]. Figure 11 shows force direction in the trusses of a truss cantilever bridge.

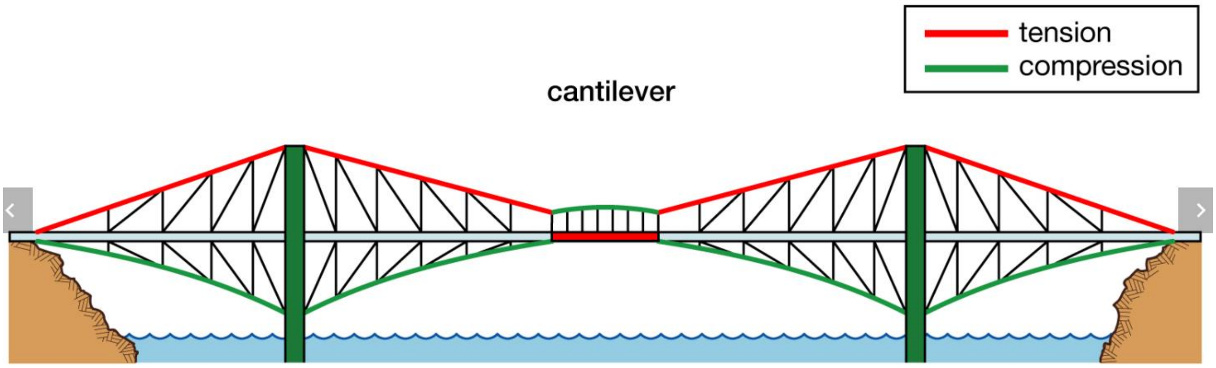


Figure 11: Layout of a truss- cantilever bridge [16]

3.2 Composite Bridge Deck

Composite bridge decks are either steel box or I- girder bridge with concrete decking. This type of bridge is called steel-concrete hybrid bridges. The cross section consists of two or more materials such as steel, concrete and wood. Typically for steel- concrete hybrid bridges are a top deck made of concrete laid upon steel beams. In order to maximize the effect of the contribution from each material to withstand the forces, it is necessary to create a bond where the shear forces can be transferred [17].

When the concrete deck is placed upon a simply supported steel beam it will bend about its own axis under loading. This will give an elongation between the concrete end and beams end on both sides, as shown in figure 12. The stiffness will therefore be the stiffness contribution from each material [17].

In order to achieve a greater total stiffness, it is necessary to transfer the forces between the elements. This can be done by welding spikes at the top flange of the beam before casting the concrete deck. The spikes work as a friction joint between the concrete and the steel and distributes the shear forces [17].

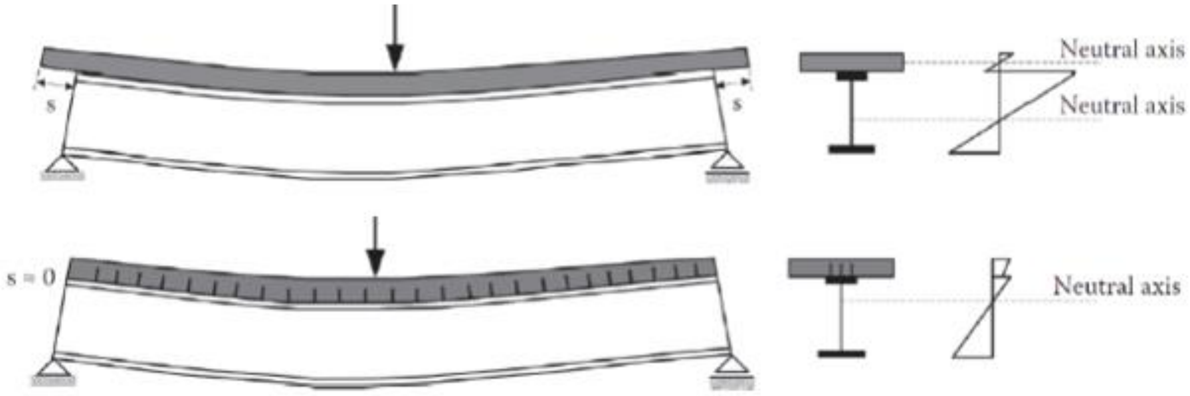


Figure 12: Top- No connection between the materials. Can see the elongation at the ends Bottom- Spikes welded at the top flange of the steel beam which create a friction bond [17]

3.2.1 Plate Girder composite Bridge

When seismic loadings, braking forces, and other forces are applied to the deck slab, it works as a diaphragm. As a result, the slab's thickness must be sufficient to ensure acceptable out-of-plane and in-plane stiffness. The slab thickness varies from 25 to 30 cm, depending on the girder spacing a, which typically ranges from 2.5 to 4.0 m. Figure 13 shows a typically cross-section for a plate girder composite bridge. It is preferable to adopt a girder spacing that is not greater than the effective width, as determined by EN 1994-2 requirements, so that the entire concrete slab contributes to the superstructure's structural performance [17].

S355 is the most popular structural steel grade, however S420, S460, and even S690 have already been adopted in various European countries. C30/37 and C35/40 are the most suitable concrete qualities for the in-situ components of the deck. By far the most popular construction method is the use of full in situ concrete deck slabs. A mobile formwork runs along the steel beams concreting sections with a maximum length of 25 m. Because of the noncomposite action during concreting, this approach has several drawbacks, including a long execution time, high shrinkage forces, and the usage of a considerable amount of structural steel. In many circumstances, the most cost-effective method is to pour the deck slab on temporary soft formworks, usually constructed of wood, and support it with supporting towers [17].

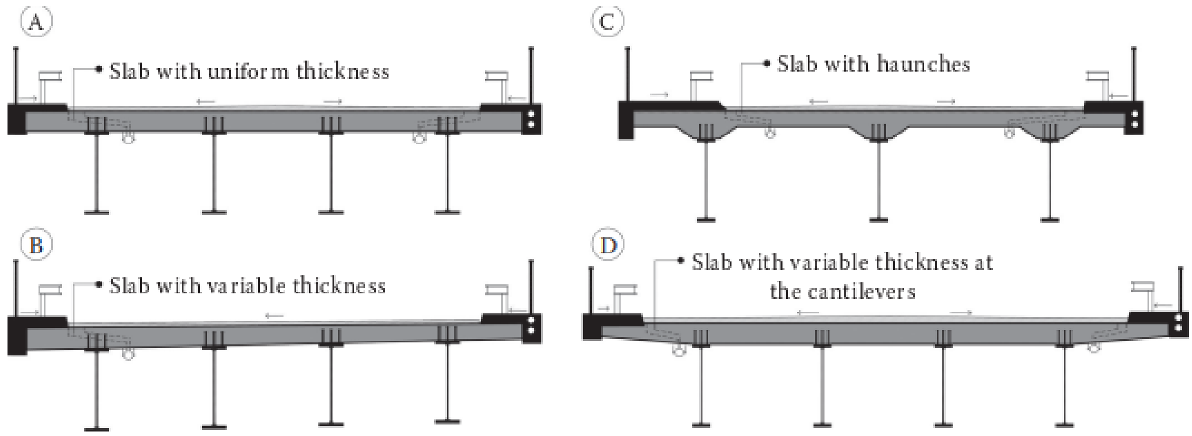


Figure 13: Different types of slabs for a girder composite bridge [17]

3.2.2 Box girder composite bridge

A single open-box girder is often the most cost-effective and aesthetically pleasing alternative for continuous bridges with a span length greater than 50 m [17]. The box girder has a trapezoidal shape, as shown in figure 14, and is made from a wide bottom flange with longitudinal stiffeners that prevent plate buckling owing to severe compression loads that may occur during the final and/or erection stages [17].

The webs are quite angled, with the angle ranging between 15 and 25 degrees. This improves the appearance of the cross section. The web's inclination is also significant for the following reasons [17]:

- The smaller width of the bottom flange improves structural performance because the shear lag effect makes a smaller portion of the flange ineffective. It also simplifies plate buckling verification and allows for the use of fewer stiffeners.

- Because the distance between the bearings is reduced, transverse frame bending at supports is easier to manage.

- Smaller abutments can be created, allowing for a slenderer substructure to be built.

When comparing the thickness of the bottom flange at the supports to the thickness at the span, the thickness at the supports is larger. This is owing to the concrete's zero tension capacity and high support reactions. The bottom flange thickness typically ranges between 25 and 35 mm along the span and between 60 and 80 mm at supports [17].

The web thickness varies longitudinally as well, ranging from 14 to 18 mm at spans to 20–25 mm at supports. The values can only be achieved by using longitudinal stiffeners that can withstand high shear and normal stresses. At spans, the thickness of the top flanges ranges from 20 to 40 mm, while at supports, it might reach 100 mm. The width of the flanges at spans ranges from 600 to 800 mm, while the width at supports may reach 1200 mm [17]

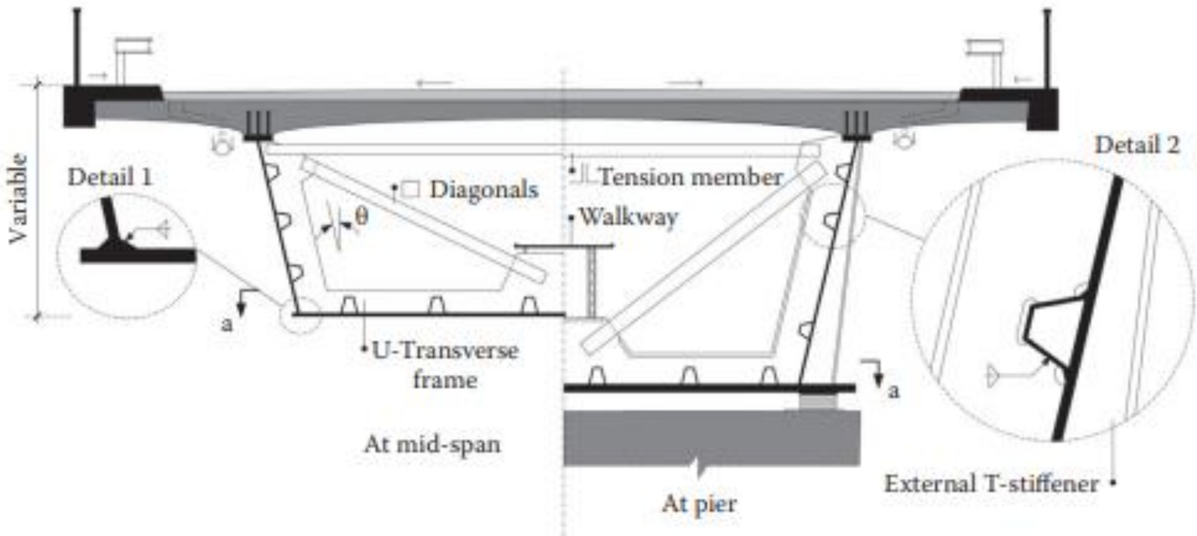


Figure 14: Cross section of box girder bridge [17]

For spans up to 50 meters, composite bridges with several girders can be used. Twin-girder bridges are more cost-effective and easier to build over longer spans. Box girder bridges are typically used for spans greater than 80 meters due to their higher flexural and torsional strength. They are less economical for small and medium spans; hence cheaper alternatives should be chosen. One of the biggest drawbacks of box girder sections is the massive sections that need to be repainted due to corrosion, which drives up maintenance expenses. Furthermore, repainting is time consuming and can be dangerous if it is done while the bridge is operational [17].

3.2.3 Double Composite bridges

The purpose of composite bridges is to exploit the higher stiffness and capacity for the cross section. This can be developed even further by the double composite cross-section. In double composite bridges concrete are cast at the bottom of the box girder above the pillars where negative moments will be taken up by the concrete rather than the bottom steel flange [18].

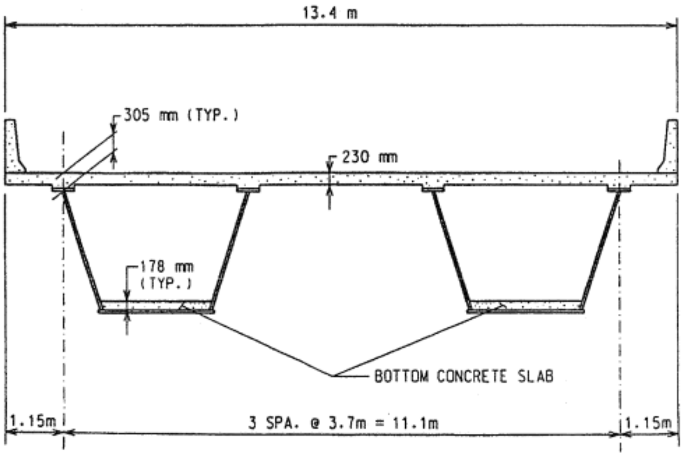


Figure 15: Cross-section of double composite bridge [19].

This method where some parts of the steel is replaced by concrete, is more economical compared to regular composite bridges. In additional it will give better stiffness, moment distribution, reduced deflection, torsional capacity and weight reduction [19] as shown in table 3.

Table 3: Comparison of weight and cost of composite and double composite bridge [19]

Basis of Comparison	"Conventional" Plate Girder	Double-Composite Plate Girder	Double-Composite Box Girder	% Savings for Double-Composite Plate Girder Design
Weight of Girder [note 1]	2144 kN	1911 kN	1946 kN	12%
Unit Weight of Structural Steel	284 Kg/m^2 (58.1 lb/sf)	253 Kg/m^2 (51.8 lb/sf)	257 kg/m^2 (52.8 lb/sf)	12%
Total Superstructure Cost	$2,514,472	$2,379,211	$2,525,227	6%
Superstructure Unit Cost	$816/m^3 ($75.85/sf)	$772/m^3 ($71.76/sf)	819/m^3 (76.16/sf)	6%

note 1: Weight of one girder, including cross frames (or one-half of a box girder)

3.3 Balanced cantilever concrete bridge

Balanced cantilever bridge is a bridge type that is well suited for spans of 100-400 meters [20]. Norway's first balanced cantilever bridge was Tromsøbrua [21]. It was common to have a joint at the middle of two spans in order to have a static determined system and less complex calculations, but because of deflection at the joint it is more common to construct the bridge with a continuous span even though the bridge becomes a static undetermined system [22].

Figure 16: Balanced concrete cantilever bridges during construction [22]

The building method for a balanced cantilever bridge is a cantilever which is cast outwards from the column. It can either be a single arm or double arm cantilever. The most common is the double arm method in order to achieve equilibrium at the column [22].

Since balanced cantilever bridges support themselves during construction, they are well suited for water crossings where column placement is restricted or other places where the foundation conditions are poor. During the construction period the columns must withstand both the moment from the bridge decks and torsional wind forces. The bridge column is constructed with a vertically sliding formwork. The bridge deck is cast sectionally as a box girder bridge

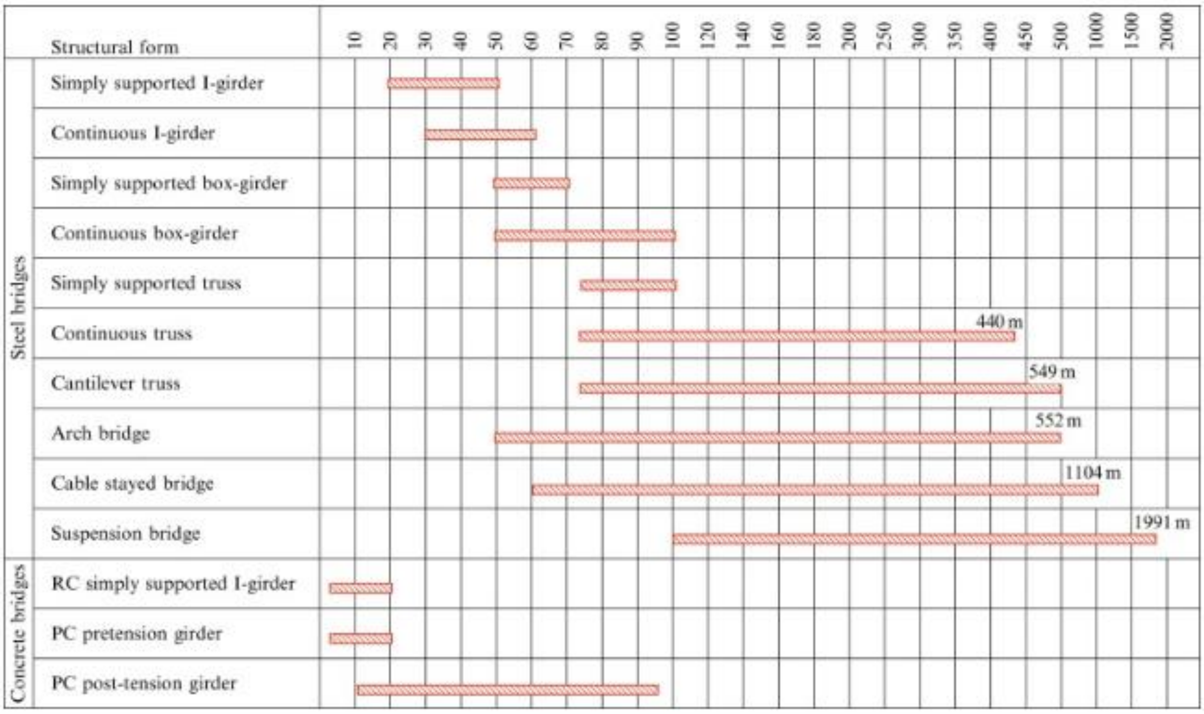
and since the box girder height warries, the formwork must be adjusted for each section. Since the bridge deck works as a cantilever the box girder cross section height is greatest near the columns and becomes narrower towards the end.
Cantilever bridges have many casting processes, different loading stages and undergo a change from static determined during construction to static undetermined during the operational phase. Therefore, there will be different projecting challenges that's need to be considered [22].

3.4 Selection of bridge design

Because the dead weight of a bridge affects its load carrying capacity, bridge superstructures are made of steel rather than concrete for long span bridges. Concrete, like stone, is a brittle material that is strong in compression but weak in tension, making it susceptible to cracking when bent or twisted. Concrete must be reinforced with steel to increase its ductility, and its development naturally coincides with that of steel. Concrete, on the other hand, will be an ideal material for some structural types of bridges, such as arch bridges whose components are primarily under compression. Concrete bridges are also commonly utilized for short-span bridges due to their inexpensive cost and low maintenance requirements in service [12].

The mechanical features of each bridge type are the deciding factor in determining the span capacity. Simply supported bridges are the easiest to construct, are statically determined, and are often ideal for small spans. Rigid-frame bridges and arch bridges are the most cost-effective alternative for span length when an unyielding foundation is available. Continuous girder bridges, truss bridges, and arch bridges are all viable options for medium-span bridges. The cable-stayed bridge and suspension bridges are promising options for wide span bridges longer than 500 meters. For spans up to 600 meters, a cable-stayed bridge is the best option. However, for bridges with span lengths greater than 1000 meters, a suspension bridge is still the best option [12]. Table 4 shows which bridge designs are most suitable based on span length.

Table 4: Most suitable bridge design based on length of span [12]



4. Materials

4.1 Concrete

Concrete is the most widely used building material in the modern world, with consumption estimated to be double that of all other materials combined [23].

The cement paste used in concrete is formed by combining Portland cement with water. The surface of the sand, gravel, and rocks will be coated with this mixture. When the paste is hydrated, it hardens and binds the aggregates together, forming concrete. The components for concrete are mixed in a weighted ratio. To ensure the performance, it must be precise [24].

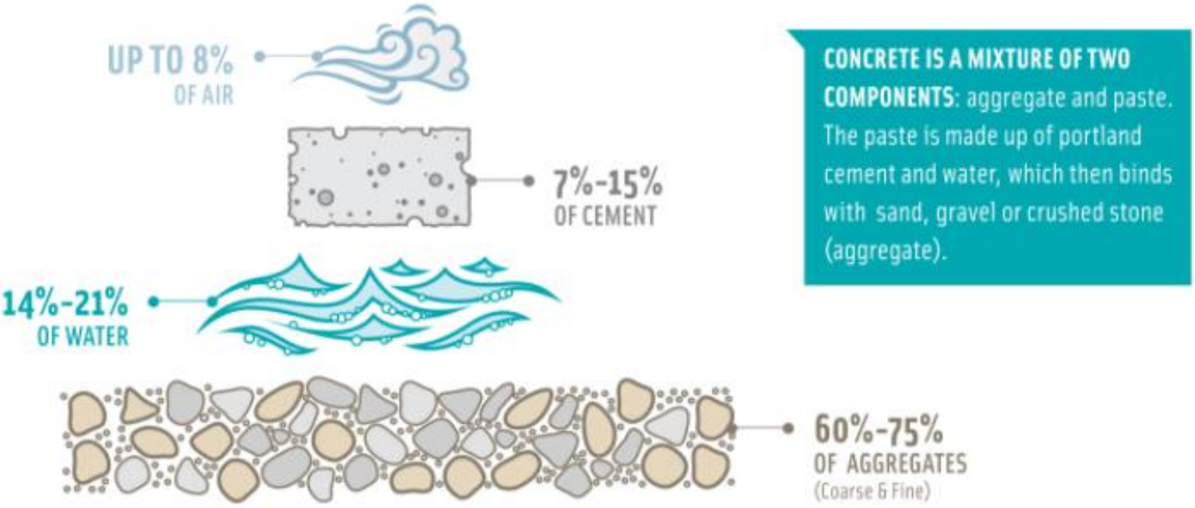


Figure 17: Compositions of the different components in concrete [24]

Other chemicals are usually added to improve material performance. These compounds have a significant impact on the overall qualities of the concrete despite their little quantities. The components used in concrete in Norway are typically 1% of the cement weight [25].

Table 5, derived from NS- EN 934-2, lists the various kinds of chemicals and their functions.

Table 5: Concrete additives and their functions [19]

Klasse tilsetningsstoff	Beskrivelse av stoffets virkemåte i betong
Vannreduserende eller plastiserende	Reduserer vannbehovet i en gitt betongblanding uten å påvirke konsistensen, eller øker synkmålet/utbredingsmålet uten å påvirke vannbehovet, eller har begge virkningene samtidig
Sterkt vannreduserende eller superplastiserende	Reduserer vannbehovet *vesentlig* i en gitt betongblanding uten å påvirke konsistensen, eller øker synkmålet/utbredingsmålet vesentlig uten å påvirke vannbehovet, eller har begge virkningene samtidig
Luftinnførende	Tilfører en kontrollert mengde av små, jevnt fordelte luftbobler under blanding, som blir værende etter herding
Størkningsakselererende	Reduserer tiden før betongblandingens overgang fra plastisk til stiv tilstand
Herdingsakselererende	Fører til raskere utvikling av tidlig fasthet i betong, med eller uten innvirkning på størkningstiden
Størkningsretarderende	Øker tiden før betongblandingens overgang fra plastisk til stiv tilstand
Vannavstøtende	Reduserer det kapillære vannopptaket i herdet betong
Stoff for redusert vannutskillelse	Reduserer vanntapet ved å redusere vannutskillelsen («bleeding»)
Størkningsretarderende og vannreduserende	Gir kombinerte virkninger av et vannreduserende stoff (primærfunksjon) og et størkningsretarderende stoff (sekundærfunksjon)
Størkningsretarderende og sterkt vannreduserende	Gir kombinerte virkninger av et *sterkt* vannreduserende stoff (primærfunksjon) og et størkningsretarderende stoff (sekundærfunksjon)
Størkningsakselererende og vannreduserende	Gir kombinerte virkninger av et vannreduserende stoff (primærfunksjon) og et størkningsakselererende stoff (sekundærfunksjon)

Although concrete has numerous advantages, it also has certain disadvantages. Concrete can be hazardous to employees' health, causing irritation, concrete burns, and dermatitis when they come into close contact with it [26].

The significant amount of CO2 gases produced during cement manufacture, which is estimated to account for 5-7 percent of worldwide CO2 emissions, is the major negative consequence of concrete. In most cases, the weight ratio of CO2 emissions to cement produced is 1 to 1, or 300 kg CO2 per m3 concrete [27]. Figure 18 shows the amount and where during manufacturing of cement the emissions are released.

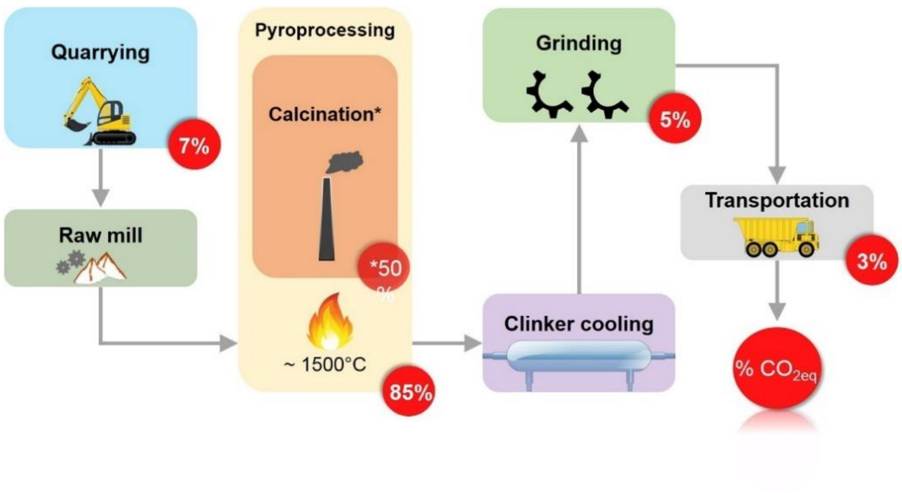


Figure 18: CO2 emissions during the different stages of cement production [27]

4.1.1 Types of concrete

Depending on the characteristics and requirements the concrete must fulfill, there are many different types of concrete that can be used. Changing the water-cement ratio can alter the concrete's strength, durability, heat resistance, and workability [28].

The durability class for concrete is determined by the exposure class which is based on the concrete structures risk of corrosion, carbonation, freeze and thaw and chemical attacks.

Table 6 shows the exposure and durability class.

For bridges in Norway, the Norwegian road authority has determined what kind of concrete that can be used for bridge constructions and which durability class they need to fulfill [29]:

- SVV- Standard: MF40 (M40 on project basis)
- SVV- Kjemisk: MF40 (M40 on project basis)

- SVV- Lavvarme: MF45

Table 6: Exposure and durability classes [29]

TABELL 1:

Klassifisering av konstruksjoner ut fra miljøbelastning Grad av belastning angis med nummer. For en mer detaljert oversikt av klasseinndelingen og beskrivelse av miljø, samt eksempler på hvor eksponeringsklassene kan forekomme, henvises det til NS-EN 206:2013+NA:2014	
EKSPONERINGSKLASSER	
XO	Ingen risiko for korrosjon eller angrep
XC1-4	Korrosjon framkalt av karbonatisering
XD1-3	Korrosjon framkalt av klorider som ikke stammer fra sjøvann
XS1-3	Korrosjon framkalt av klorider fra sjøvann
XF1-4	Fryse-/tineangrep
XA1-4	Kjemisk angrep
XSA	Særlig aggressivt miljø

TABELL 2:

Bestandighetsklassene med tilhørende eksponeringsklasser og materialkrav Valg av bestandighetsklassene etter nasjonalt tillegg til NS-EN 206:2013+NA:2014						
EKSPONERINGSKLASSE	**BESTANDIGHETSKLASSE**					
	M90	**M60**	**M45**	**MF45[3)]**	**M40[4)]**	**MF40[3,4)]**
X0	X	X	X	X	X	X
XC1, XC2, XC3, XC4, XF1		X	X	X	X	X
XA1, XA2[1)], XA4[2)], XD1, XS1			X	X	X	X
XF2, XF3, XF4				X		X
XD2, XD3, XS2, XS3, XA3[1)]					X	X
XSA[1)]	Betongsammensetning og beskyttelsestiltak fastsettes særskilt. Betongsammensetningen skal minst tilfredsstille kravene til M40					
Største masseforhold v/(c+Σk p)	0.90	0.60[5)]	0.45	0.45	0.40	0.40
Minste luftinnhold i fersk betong	-	-	-	4%	-	4%
Minste effektive bindemiddel-mengde (c+Σk p) kg/m³)	225	250	300	300	330	330
Tillatte sementer	STD FA ANL FA ANL IND	STD FA ANL FA ANL IND	STD FA ANL FA ANL IND	STD FA ANL FA ANL IND	STD FA ANL FA ANL IND	STD FA ANL FA ANL IND

1) Om det i eksponeringsklasse XA2, XA3 eller XSA er mulighet for kontakt med sulfater i konsentrasjoner høyere enn nedre grenseverdien for XA2, skal det i produksjonsunderlaget presiseres at det skal anvendes sulfatbestandig bindemiddel. (Tabell NA.13 i NS-EN 206:2013+NA:2014)
2) For konstruksjoner utsatt for husdyrgjødsel, skal det i produksjonsunderlaget presiseres at det skal anvendes minst 4% silikastøv.
3) For bestandighetsklasse MF45 og MF40 skal det anvendes frostsikkert tilslag.
4) Bindemidlet skal minst inneholde 6% silikastøv.
5) For STD FA og ANL FA er største masseforhold i M60 henholdsvis 0,54 og 0,55.

4.1.2 Low carbon concrete

Concrete is one of the most used materials in the construction industry, it is also one of the materials standing for the most CO_2 emissions in the world. This has led to new concrete recipes to reduce the CO_2 emissions. Low carbon concrete is a concrete produced according to the rules in NS-EN 206 and is categorized after requirements of the CO_2 emissions defined in the publication from Norsk Betongforening. The low carbon concrete is divided into classes, which contains of [30]:

- Low carbon B - Ordinary prescribed technical measures are generally sufficient
- Low carbon A - Usually requires the use of special prescription technical measures
- Low carbon Pluss and Extreme - Requires the use of special binder compositions that cannot be expected to be widely available, and with several limitations in the standard work

The different requirements for CO_2 emissions of each type of Low carbon concrete are given in table 7 [30].

Table 7: Low-carbon concrete classes with limit values for greenhouse gas emissions [30].

Strength class and low carbon class	B20	B25	B30	B35	B45	B55	B65
Maximum allowed greenhouse gas emissions [kg CO2-eqv. Pr m^3 concrete]							
Industry reference	240	260	280	330	360	370	380
Low carbon b	190	210	230	280	290	300	310
Low carbon A	170	180	200	210	220	230	240
Low carbon Plus			150	160	170	180	190
Low carbon Extreme			110	120	130	140	150

In today's use of low carbon concrete, there is still no procedure for classification of prefabricated elements according to the low carbon concrete classes. When it comes to getting elements with bigger portions of fly ash than normal, to acquire the highest classes of low carbon concrete like class A, is not widespread among suppliers. Prefabricated elements will most of the time not be able to use big portions of fly ash to achieve class A. The reason for that is the hydration time, early firmness, demoulding time and rock mass with maximal grain size D_{max} [30].

The use of low carbon concrete in the winter is possible with some challenges. Low carbon B and A could be used as winter concrete with ordinary measures. But when it comes to Low carbon Plus and Extreme, there is a need for extra measures. Like the use of isolation materials or firing. If the reduced heat- and strength development must be compensated by firing, and increased temperature in the concrete or if other energy demanding measures are done, it needs to be taken in the total green gas emissions accounts [30].

4.1.2.1 Challenges

Low carbon concrete with the use of high portions of additional materials could give production technical challenges, when it comes to propulsion and buildability. Slag, fly ash and silica will all influence the concrete differently and could give rash in [30]:

- Slower strength development
- Increased temperature sensitivity
- Reduced heat generation
- Changed final strength

Figure 19 shows the availability of low carbon concrete in different parts of Norway. The different zones show the sum of the availability and how it affects the concrete's greenhouse gas emissions in an area, when it comes to binders, transport of raw materials and aggregate quality. The zones should not be considered as exact, but more as an indication. The first zone is where the possibilities to get lower green gas emissions is the highest. In zone 5 it is quite the opposite, and it will have high green gas emissions. It would be possible to achieve low carbon concrete class A in several zones, but the best zone for this is zone 1 [31].

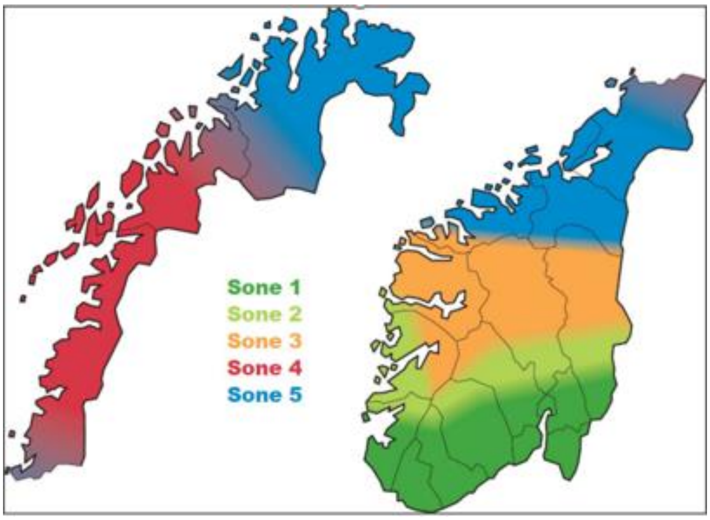


Figure 19: regional availability of low-carbon concrete. Zone 1 has the best accessibility, zone 5 the worst [30].

4.1.2.2 The development of strength

Concrete must not freeze until it has acquired a strength of 5 MPa, according to NS-EN 13670: 2009 + NA: 2010 [32]. We also need to know how strength develops in order to decide whether prestressed constructions can be tensioned. The higher the hardening temperature, the more porous the concrete becomes, making it less durable and having a lower final strength. The temperature must not exceed 70 degrees Celsius, according to NS-EN 13670: 2009 + NA: 2010 [32]. This requirement is based on the fact that at higher curing temperatures there may be a risk of "delayed ettringite formation". It should be checked that there are no excessive temperature differences between the interior of the concrete and the surface of the concrete, or between the surface and the air when the formwork is demolished. In both cases, cracks can occur in the concrete [33].

Concrete casting in frost and winter circumstances should only be done when all the required aids for ensuring the concrete's quality and a comfortable temperature during mixing, casting, and hardening are present and ready to use before casting begins. The NS-EN 13670: 2009 + NA: 2010 [32] standard specifies the following standards for concrete casting in the winter:

- Primer, formwork, or structural elements must not have a temperature that causes the concrete to freeze until it has sufficient rolling strength to sustain damage.
- If the ambient temperature is projected to be below 0°C at the time of casting or during the curing period, special care must be taken to safeguard the concrete from freezing damage.
- Before the concrete reaches a strength of at least 5 MPa, precautions must be taken to guarantee that the temperature of the concrete never falls below 0° C.
- The temperature of fresh concrete shall not be lower than 5° C when delivered to the construction site, according to NS-EN 206.

Table 8: Shortest period of casting measurements in days for casting class 2 [32]

Betongoverflatetemp (t) °C	Minste periode med herdetiltak i døgn [a)]		
	Utvikling av betongfasthet [c) d)] $(f_{cm2} / f_{cm28}) = r$		
	Rask r ≥ 0,50	Middels rask 0,50 > r ≥ 0,30	Langsom 0,30 > r ≥ 0,15
t ≥ 25	1,0	1,5	2,5
25 > t ≥ 15	1,0	2,5	5,0
15 > t ≥ 10	1,5	4,0	8,0
10 > t ≥ 5 [b)]	2,0	5,0	11

a) Pluss avbindingsperioder som overskrider fem timer
b) Har betongtemperaturen vært lavere enn 5°C i deler av perioden, bør varigheten av herdetiltakene utvides tilsvarende
c) Utviklingen av betongfastheten er forholdet mellom midlere trykkfasthet etter to døgn og midlere trykkfasthet etter 28 døgn, bestemt fra initiell prøving eller basert på deklarasjon fra betongprodusenten (se NS-EN 206-1)
d) For betong med meget langsom fasthetsutvikling bør det angis spesielle krav i produksjonsunderlaget.

4.1.2.3 Final strength

Low carbon class A has a slower development of strength than ordinary concrete. This can affect the progress of a project in that the journey must be longer, the loading time must be postponed, etc. For concrete with a high proportion of additives (higher than 25-30%), the slow strength development will mean that the time for checking the concrete compressive strength should be changed [32]. Today, the compressive strength of the concrete is documented after 28 days in a 20-degree water bath. In future revisions of European standards, there is an agreement that the compressive strength of the concrete should be checked after 90 days, precisely to capture the increase in compressive strength after 28 days. When using low-carbon concrete A or better, it is highly relevant to provide rules for checking the compressive strength of the concrete after 28 days. The Norwegians road authority handbook *Prosesskode 2* [29] has set the control age of the concrete at the identity test to 56 days for SVV-Lavvarme. This should also be possible for Low Carbon Concrete [33].

Table 9: Duration of curing measures for curing class 3 and 4 [32]

Betongtype	Betongoverflatetemperatur							
	≥25 °	25 -15°C	15 - 10°C	10 - 5°C	≥25 °	25 - 15°C	15 - 10°C	10 - 5°C
	Dager med herdetiltak for herdeklasse 3				Dager med herdetiltak for herdeklasse 4			
Lavkarbon B og C (hurtig)	1,5	2	2,5	3	3	5	7	9
Lavkarbon A (middels)	2,5	4	7	9	5	9	13	18
Lavkarbon A (langsom)	3,5	7	12	18	6	12	21	30

To make the casting time shorter, substances could be used in the concrete. X-Seed is a substance that can be used with all types of EN 197-cements. It helps maintain the development of strength and helps to reduce the content of cement in the concrete mix. The product is suitable for larger constructions with solid concrete or concrete elements where it is crucial with low heat during concrete hardening [34].

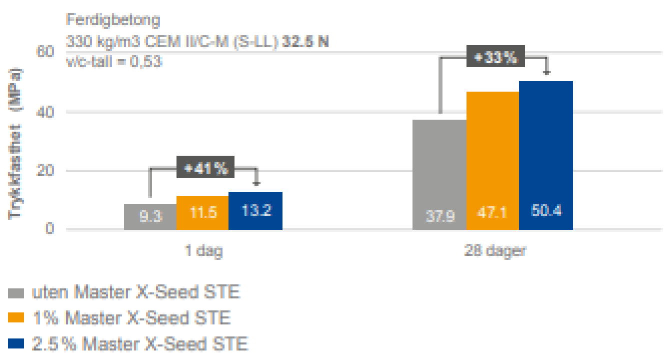


Figure 20: Strength development for low carbon concrete based on X-seed content [34]

The casting time when using X-Seed could improve with 41% as shown in figure 20. Which can make the low carbon concrete more usable in several cases, without making it less environmentally friendly.

4.1.4 High-performance concrete- HPC

According to Byggforskserien 572.205 high performance concrete, HPC, can be determined as concrete with quality higher than B50 [35].
The distinguishing features between normal and high strength concrete have varied over time and with changes in history. A concrete having a compressive strength of 28 MPa was regarded as a high strength concrete 100 years ago [36].

Due to its excellent features like high strength and durability, high-performance concrete has a variety of uses in civil engineering.
Bridges, hydroelectric structures, offshore platforms, tunnels, and high-rise structures are examples of where high-performance concrete has been utilized. HPC in bridge construction provides several structural advantages. For example, it increases the structural durability and thus the life duration of the constructions. Furthermore, when high-performance concrete is used, greater span prestressed concrete girders can be built. This is because such concrete has a lower loss in pre-stress, resulting in a higher allowed stress and a smaller cross-section [37].

For Norwegian supplier it can be difficult to produce concrete greater than B55 due to lack of cement with enough strength properties [35]. Therefore, other solutions would be to:

- Reduce the water/cement- ratio
- Use of silica dust
- Avoid air entrainer in the concrete
- Use gravel with higher strength properties

Even though HPC has advantages like high strength and durability there are also some disadvantages like [35]:

- More demanding casting properties
- Higher risk plastic shrinkage cracks
- High heat development which can cause risk of early cracks

4.1.5 Concrete CO_2-emissions

Every year, 30 billion tons of concrete are utilized around the world. That is three times what it was 40 years ago, and concrete consumption is expanding faster than steel or wood.

Concrete buildings and structures are versatile and long-lasting, making them excellent for climate-resilient construction in many ways. However, concrete has a massive carbon footprint: the cement sector accounts for at least 8% of all human-caused global emissions. Its manufacture must be decarbonized [38].

It is not only the production of concrete which leads to these emissions, but different factors in the total picture of the use of concrete has also their emissions. The cement that is used is one of the big factors, but transportation also has a role.

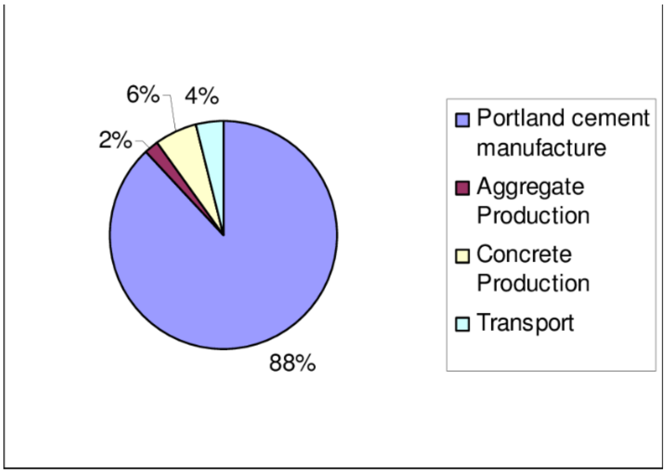


Figure 21: CO_2 emissions from concrete by category [39]

4.1.5.1 EPD for concrete

The use of EPD's gives a good picture of products and services environmental impacts when constructing something. When you have several different suggestions, it is beneficial to use an EPD to clearly see which solution is the most correct. The EPD consists of different life parts of a construction, and it is divided into 5 parts. A1-A5 is the product stage and construction installation stage. B1-B7 is the user stage, while C1-C4 is the end-of-life stage of the construction. In the end is part D, which is for boundaries beyond the system as mentioned in chapter 2.2.1.

On average the lowest GWP for concrete B35 M45 in stage A1-A3 varies from $237{,}82\ kg\ CO_2 - eqv$ to $282{,}35\ kg\ CO_2 - eqv$ for one ton concrete. Three EPD's from three different concrete distributors have been analyzed which has given this data:

- Concrete B35 M45 from Velde Betong AS $237{,}82\ kg\ CO_2 - eqv$ [40]

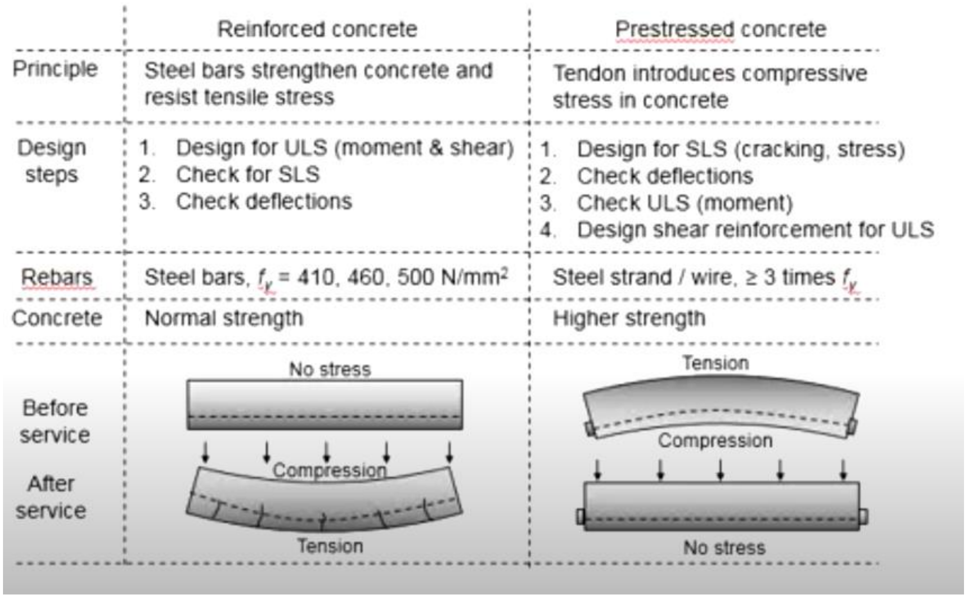
- Concrete B35 M45 from Betong Øst AS $239{,}91\ kg\ CO_2 - eqv$ [Appendix G]

- Concrete B35 M45 from Sylteosen Betong AS $282{,}35\ kg\ CO_2 - eqv$ [41]

4.2 Reinforcement

Reinforcement is used in concrete to increase the resistance in the cross section. There are two ways to use reinforcement in concrete. The reinforcement could be added with or without tension in the concrete, with both ways giving different properties to the concrete. The reinforcement steel should have high strength, satisfying ductility and necessary adhesion for the properties of the cross section to be good enough. To get this the steel is dimensioned with a nominal diameter. The reinforcement steel could come from completely new steel, or it could be recycled steel [42].

The other way to use reinforcement in concrete is to tense the steel before buckling it in place. By doing this, we get a pre-stressed concrete. The reinforcement could be tensioned before or after buckling it in place. If it is done before the reinforcement is tensioned before the concrete is cast, in a factory. The other way is to tense the steel after the concrete is cast and has sufficiently hardened. This method is mostly used on cast in place constructions, like the bridge Kjøkøysund bridge addressed in this thesis. When post-tensioning the reinforcement lays in recess channels in the precast concrete with anchors on both sides. Even though the anchors could be either passive or active, it is most common to put one passive anchor on one end and one active on the other. There is also a possibility to use active ones. The reinforcement is tensioned with a jack in the active anchor, while using the concrete structure as the support [42].



	Reinforced concrete	Prestressed concrete
Principle	Steel bars strengthen concrete and resist tensile stress	Tendon introduces compressive stress in concrete
Design steps	1. Design for ULS (moment & shear) 2. Check for SLS 3. Check deflections	1. Design for SLS (cracking, stress) 2. Check deflections 3. Check ULS (moment) 4. Design shear reinforcement for ULS
Rebars	Steel bars, f_y = 410, 460, 500 N/mm²	Steel strand / wire, ≥ 3 times f_y
Concrete	Normal strength	Higher strength
Before service After service	No stress Compression Tension	Tension Compression No stress

Figure 22: The differences between the reinforcement methods [42]

4.3 Steel

4.3.1 Steel production

Steel can be produced in two different methods. The procedures are classified based on the raw material used in the process. Steel manufactured from iron ore is made with blast furnace-based production, BF, while scrap steel from recycled steel is produced by electric arc furnace, EAF. We are now reliant on both scrap steel and steel made from iron ore, as scrap accounts for around 30% of the demand for new steel. Scrap-based steel is expected to account for around half of demand in 2050, which means that steel made from iron ore will continue to meet half of demand [43].

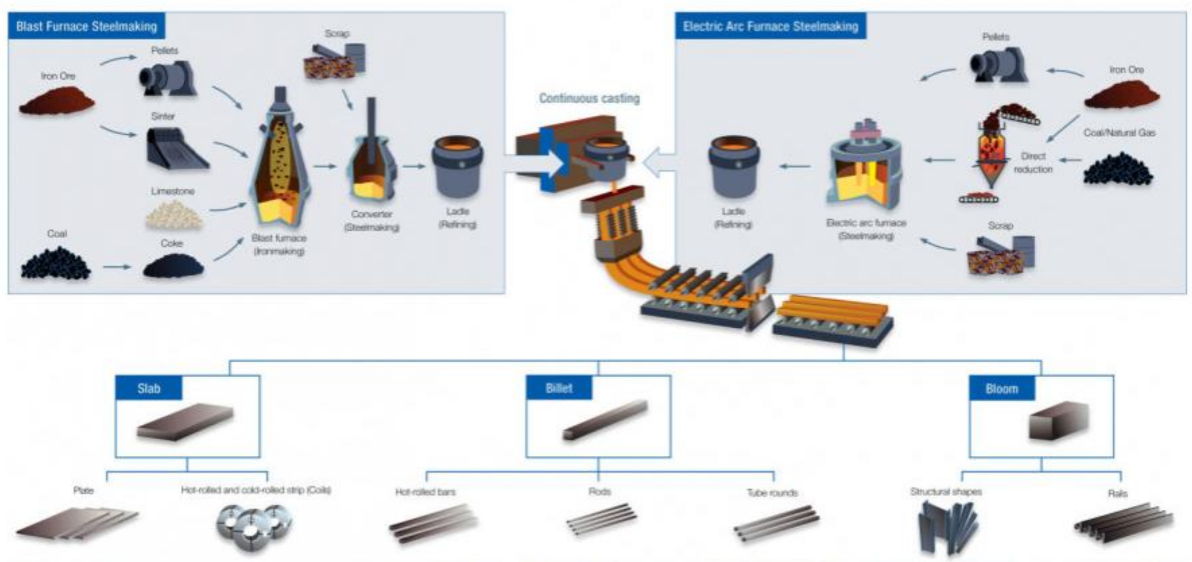


Figure 23: Steel production [44]

Steel is recyclable and is the world most recycled product. A major reason is the internationally and well-functioning market for scrap steel. Since there are incentives beyond the economical ones the scrap steel production is sustainable [45].
Steel production accounts for 7% of the world's CO_2 emissions. By using steel manufactured from scrap steel one can reduce the energy and emissions by respectively 60% and 70 % [45].

Steel is an internationally traded resource that is manufactured all over the world. Steel production in the world totaled 1.9 billion tons and has been increasing since 2009, as shown in figure 24, owing primarily to increased Chinese production and consumption. Although this global trend, EU production remains below pre-crisis levels from 2008 [44].
China dominated the global steel production in 2019, producing more than half of the world's steel (996 million tons or 53 percent). Asian countries produced about three-quarters of the world's steel. The EU was the world's second largest steel manufacturer, accounting for 8.5 percent (159 million tons), behind India, Japan, the United States, Russia, and South Korea [44].

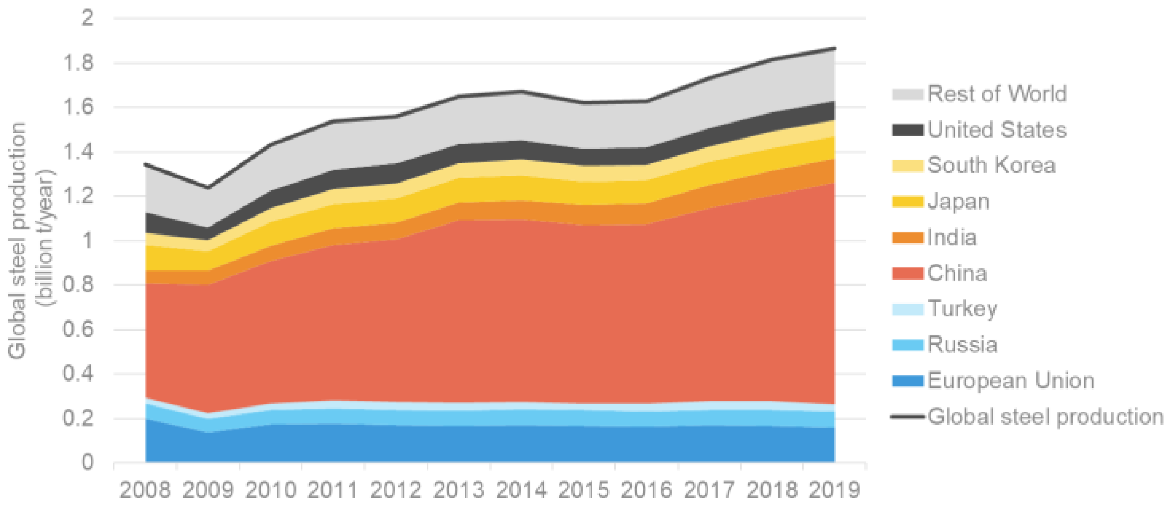


Figure 24: Global steel production [44]

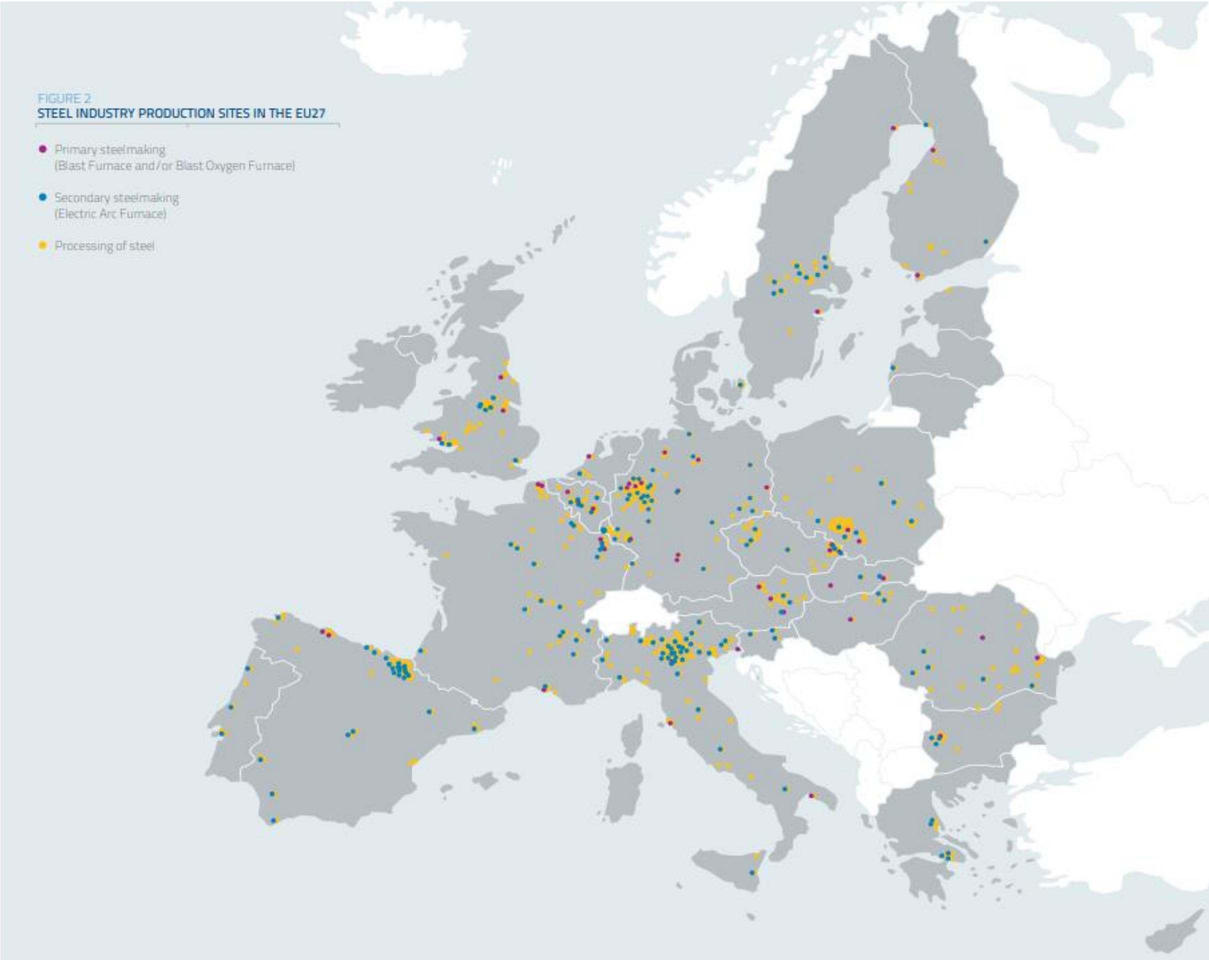


Figure 25: Steel plants in EU [44]

A study by Medarac. H, Moya. J. A and Somers. J [44] looked at 153 steel plants across 11 regions based on their steel product and production technology [44] which as shown in table 10. The integrated route (Blast Furnace and Basic Oxygen Furnace: BF-BOF) and the recycling route (Electric Arc Furnace: EAF) are both included in the study. HRC and WR (hot rolled coil and wire rod, respectively) are used as proxy items for flat and long products. Integrated and recycling paths are available at some plants. The research assumes that hot rolled coil is produced via the integrated route and wire rod via the recycling route at these plants.

Table 10: Steel plants production route [44]

153 plants observed in 11 countries		Production Routes: Integrated Route (BF-BOF) and Recycling Route (EAF)		
		BF-BOF	BF-BOF and EAF	EAF
Production of Flat Products (Hot Rolled Coil) and Long Products (Wire Rod)	Hot Rolled Coil	56 EU27 15 Russia 1 Turkey 1 UK 1 US 9 Ukraine 1 China 15 India 3 Japan 7 South Korea 1 Brazil 2	7 China 1 India 4 South Korea 1 Brazil 1	15 EU27 2 Turkey 1 US 10 Japan 2
	Hot Rolled Coil and Wire Rod	26 EU27 2 Turkey 1 China 16 India 1 Japan 4 South Korea 1 Brazil 1	7 Russia 3 China 3 India 1	0
	Wire Rod	22 EU27 3 Turkey 1 UK 1 Ukraine 1 China 13 India 2 Brazil 1	2 China 2	18 EU27 9 Turkey 2 US 5 Brazil 2

Most of EAF steel plants for hot rolled flat products are in the US while China has none even though China is the major global steel producer. The European union have two plants for steel plate production based on scrap metal which is the same number as Japan.

Even though EAF accounts for around 30% of global steel supply, it is about 10% of China's total steel production. Furthermore, Chinese EAF production includes a significant percentage of pig iron, making Chinese EAF production more energy intensive than that of many other countries. Because pig iron requires a large amount of energy to create, using it as a feedstock in EAFs can raise the total energy consumption and CO_2 emissions connected with EAF steel production [46].

4.3.2 Cost of steel production

The report from Medarac. H, Moya. J. A and Somers. J [44] analyzed the cost of EAF steel production based on the cost of components such as energy, labor and raw material. The complete list is shown in table 11:

Table 11: Cost breakdown of steel production [44]

Cost breakdown	Cost components by Moya and Boulamanti	Elements of Stacked Cost Curve in CRU Steel Cost Model 2019
Energy	Energy (Electricity and Natural gas)	Energy (Coke oven gas, Blast furnace gas, Basic oxygen furnace gas, Corex as, Custom iron gas, Custom steel gas, Heavy fuel oil, Natural gas, Thermal coal, Other fuel and Steam)
		Purchased electricity
Labour	Labour	Labour
Raw Material	Raw Material (Iron ore, Scrap, Limestone, Oxygen, Ferrosilicon and Reductants)	Iron ore (Lump ore, Sinter fines, Pellet feed, 3rd party pellet and 3rd party sinter)
		Reductants (Coking coal, Injection coal, Anthracite, 3rd party coke, Injection natural gas, Injection heavy fuel oil and Injection other fuels)
		Metallics and ferroalloys (3rd party scrap, 3rd party direct reduced iron, 3rd party pig iron, Ferroalloys, Aluminium, Zinc and Tin)
		Purchased semis (Purchased slab, purchased hot rolled coil, purchased cold rolled coil and Purchased billet)
Credit[4]	Credit (savings from recycled scrap and self-power generation)	Credits (Blast furnace gas credit, Basic oxygen furnace gas credit, Corex gas credit, Custom iron gas credit, Custom steel gas credit, Steam credit, Scrap reverts, Fe reverts, Tar, Benzole and Slag)
Other	Other (fluxes and other consumables)	Other consumables (Fluxes, Electrodes, Refractories, Oxygen, Inert gases, Industrial water, Bentonite, Cold rolling oil, Pickling acid and Paint)
		Other costs (Overheads, Sustaining capital, Interest on working capital, Rolls and roll shop, Parts and spares and other costs)
		CO_2 costs

It is worth noting that the 'other costs' group also includes CO_2 costs that are unique to the EU, the UK, and South Korea.

The costs are illustrated in figure 26 that show the weighted mean costs arranged from lowest to highest, with a vertical line showing the cost range for each country.

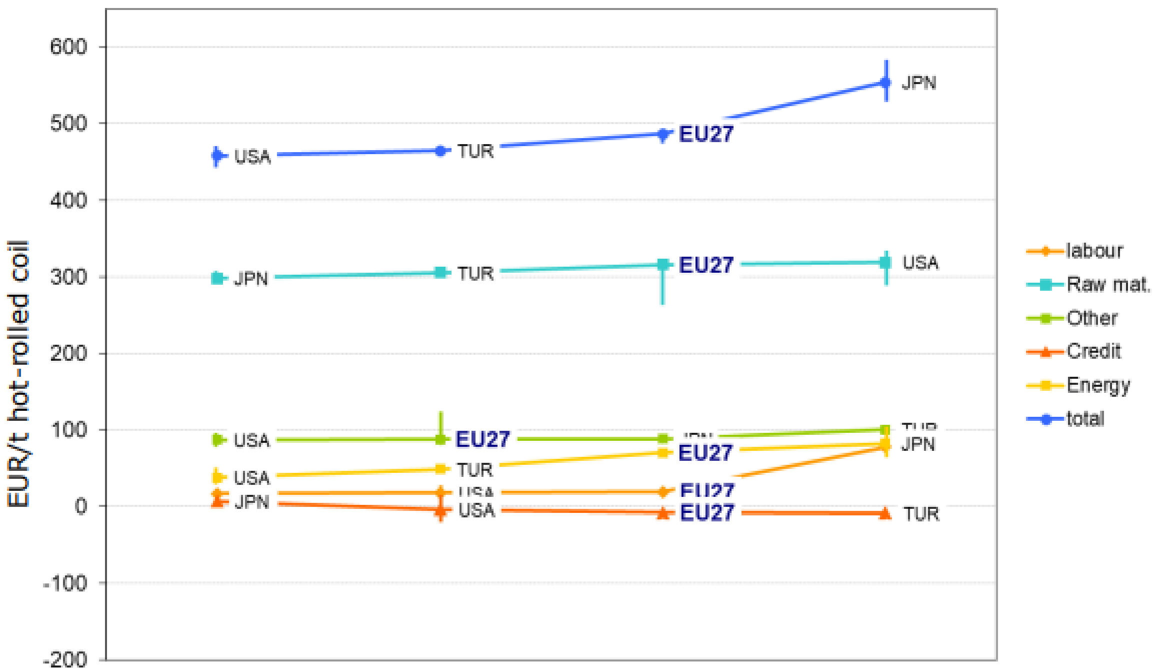


Figure 26: Steel cost in euro for each ton [44]

The data sample is taken from 15 plants and the cost variety between the countries is minimal. Other observations are:

- The raw material price is very similar for all regions with a cost of around 300 EUR/t.
- The labor cost varies from 17 EUR/t to 19 EUR/t except for Japan, where the labor cost is exceptional higher with a cost of 78 EUR/t
- The European Union has an energy cost with a price of 71 EUR/t, which is the second highest after Japan with a price of 83 EUR/t
- With a price of 0,9 EUR/t, the impact of CO_2 cost is negligible for recycled hot rolled steel.

The graphs show the breakdown of recycled hot rolled production steel. After Japan, with an average cost of 554 EUR/t, EU facilities have the second highest average production costs with 486 EUR/t. All other countries' production costs, on the other hand, are very similar. Recycled hot rolled steel is often more expensive than hot rolled steel made by iron ore due to greater energy costs and lower levels of credits from scrap materials, such as blast furnace credit and slag production, and self-generating energy.

4.3.3 Steel CO_2-emissions

For every ton of steel produced, 1.9 tons of CO_2 are emitted. The energy consumed by iron and steel production emits roughly 2.8 million tons of CO_2 per year, accounting for about 8% of the global energy-related emissions [47].

Because it maintains any pollutants that were present in the scrap steel, such as copper, steel produced in an EAF tends to be of lower quality than virgin steel [48].

Toktarova. A, et al [48] conducted a study which examined several methods to reduce the emission from steel production based on a Swedish case study. The methods are shown in table 12 with information about CO_2 intensity, cost and if the technology is commercial or not (technology readiness level- TRL). For technology, which is commercial, the EAF method has the lowest emission with 0,6 CO_2 ton/ ton steel.

Table 12: Co2 emission based on different steel manufacturing method [48]

Process	TRL Status	CO_2 Emissions, Tonne CO_2/ Tonne Steel	Capital Expenses, €/Tonne
Primary steel production			
Blast furnace with basic oxygen furnace (BF/BOF)	Commercial (TRL 9)	1.6–2.2	386–442
Top gas recycling blast furnace (TGRBF/BOF)	TRL 7	1.44–1.98	632
CO_2 capture technology [1]	TRL 6–9	CO_2 capture efficiency (%): 90	25–85
Smelting reduction (SR/BOF)	Commercial (TRL 9)	1.2–2.25	393
Direct reduction using electric arc furnace (DR/EAF)	Commercial (TRL 9)	0.63–1.15	414
Hydrogen direct reduction using electric arc furnace (H-DR/EAF)	TRL 1–4	0.025	550–900
Electrowinning (EW)	TRL 4–5	0.2–0.29	639
Secondary steel production			
Electric arc furnace (EAF)	Commercial (TRL 9)	0.6	169–184
Electric arc furnace/biomass (EAF/biomass)	TRL 6-8	0.005	169–184

[1] Capture emission points: BF, TGRBF.

Steel scrap, DRI (called sponge iron), or a combination of these resources are used as the major feedstock in EAF steelmaking. DRI manufacturing uses a reducing gas such as carbon monoxide (made from natural gas or coal) or hydrogen to convert iron ore into iron. Scrap-based EAF produces roughly 0.3 t CO_2 per t crude steel, whereas natural gas-based DRI-EAF produces around 1.4 t CO_2 per t crude steel. Coal can also be used to make DRI-EAF, with typical CO_2 emissions of 1.3–1.8 t CO_2/t crude steel [49].

The average CO_2 emissions from hydrogen-based DRI-EAF production are 0.71 t CO_2/t crude steel, while actual emissions vary greatly depending on the hydrogen production pathway. On average, it takes 9.0 GJ of energy to produce one ton of steel using the EAF steelmaking process [49]

It is worth noting that the emissions intensity of EAF steelmaking processes varies depending on the energy source and feed materials used, especially the reductant used in the DRI process. The table below shows the international energy agency assumptions on global average emissions intensity for power imported from the grid to compare the emissions intensities of major steelmaking processes [49].

Table 13: Average emission and energy consumption of steel production [49]

Steelmaking Route[8]	Average Emissions Intensity (tonnes CO_2 per tonne of steel; indirect + direct)	Average Energy Intensity (GJ per tonne of steel)
BF-BOF	2.2	20.8[9]
EAF (average)		9.0[10]
EAF (scrap-based)	0.3[11]	2.1
EAF (natural gas-based DRI)	1.4	17.1
EAF (natural gas-based DRI with CCUS)	0.57	
EAF (coal-based DRI; rotary kiln)[12]	3.2	
EAF (coal-based DRI; COREX/FINEX)[13]	1.3–1.8	
EAF (hydrogen-based DRI)	0.71[14]	

4.3.3.1 EPD for Steel

The iron production phase of the steelmaking process (stage A1) is responsible for the majority of emissions in both BF-BOF and EAF steelmaking [49].

Increases and decreases in auxiliary and supplementary materials, like paint systems, affect emissions in A3. Different product dimensions and applications will necessitate greater or fewer paint inputs [50].

4.3.3.2 Stage A1- A3

Steel recycling rates vary depending on the end-use, but on average, roughly 85 percent of steel gets recycled after it reaches the end of its first useful life. A study made in the UK showed that when a building is demolished, 94% of the steel is recycled [51].

EPD from 3 different manufacturers shows the lowest GWP for steel products for the product stages varies from 518 $kg\ CO_2 - eqv$ to 684 $kg\ CO_2 - eqv$ for one ton steel:

- Steel product from BGROUP: 518 $kg\ CO_2 - eqv$ [52]
- High strength structural steel from MetaCon: 624 $kg\ CO_2 - eqv$ [50]
- Steel from ALFA ACCIAI group: 684 $kg\ CO_2 - eqv$ [53]

Since steel is recyclable, at the end of its life one will get credit value when it becomes scrap metal [54]. Therefore, the effective GWP for one ton steel would be:

- Steel from BGROUP: $(518 - 6{,}04)\ kg\ CO_2 - eqv = 511{,}96\ kg\ CO_2 - eqv$
- High strength steel from MetaCon: $(624 - 178)\ kg\ CO_2 - eqv = 446\ kg\ CO_2 - eqv$
- Steel from ALFA ACCIAI: Non given value for benefits in stage D

4.3.3.3 Stage A4- Transportation and assembly

Since the location from manufacturing gate to building site varies from the EPD. The transport calculator provided by Østfoldforskning AS was used to calculate the GWP for transport in stage A4 which is available at www.lca.no/transportkalkulator.

The calculator is used to calculate two scenarios for environmental impact from the transport stage:

1) Environmental impact from transport stages from manufacturing site to building site.
2) Environmental impact from transport from warehouse to building site if the final destination varies from the EPD.

The calculator consists of two parts. One with pre- defines values for six different materials and one part where the distance, transport method and quantity can be manually plotted. The user manual for calculator is in the attachment.

5. Sustainable concrete constructions (SVV)

This chapter, chapter 5, will cover the report *Bærekraftige betongkonstruksjoner* by The Norwegian Road authority (SVV) [55]. The report examines the possibility to reduce the greenhouse gas emissions for constructions specified in handbook N400: *Bruprosjektering*. The constructions that are covered in the handbook are bridges, port tunnel, and piers [31]. The report compared the modern days emissions with emissions from the 1990 era and concluded it is possible to reduce the emission in all stages of the project phase.

In order to achieve the goal to reduce the emission one of the ways to go is to reduce material consumption. *Bærekraftige betongkonstruksjoner* gives an example of how to reduce the thickness of a retaining wall from 500 mm to 400 mm would give a bigger positive contribution than changing the concrete from Low carbon concrete class C to Low carbon concrete class B.

NTP 2018-2021 is a plan conducted by the Norwegian government with a goal to reduce the national emissions from construction stage with 40% and operational stage in half by 2030 [55]. This is a very optimistic goal and will be difficult to achieve in almost every project. In order to reduce greenhouse emissions, it is important to include this post as one of the factors when choosing solutions for the project. If reducing greenhouse gas emission is not written down as a requirement, then other factors will be decisive. Table 14 which requirements and factors that impacts a project.

Table 14: Requirements and factors that will influence the solution in a project [55]

Requirements	Factors
HMS	Expenses
Rules	Sustainability
Handbooks	Progression
Standards	Innovation
Environmental aspects	Form of contract

The ability to influence the emissions varies eventually based on where on the project stage the decision is made. During investigating of concept stage, where one would typically look at what kind of structure or placement, the possibility to influence the reduction of greenhouse gas emissions is bigger than later in the project. During the operational stage there are a few options besides choosing to include new technology HVAC system, water solutions, new materials when renovating and source of electricity. Figure 27 shows how the different stages can impact the overall emissions.

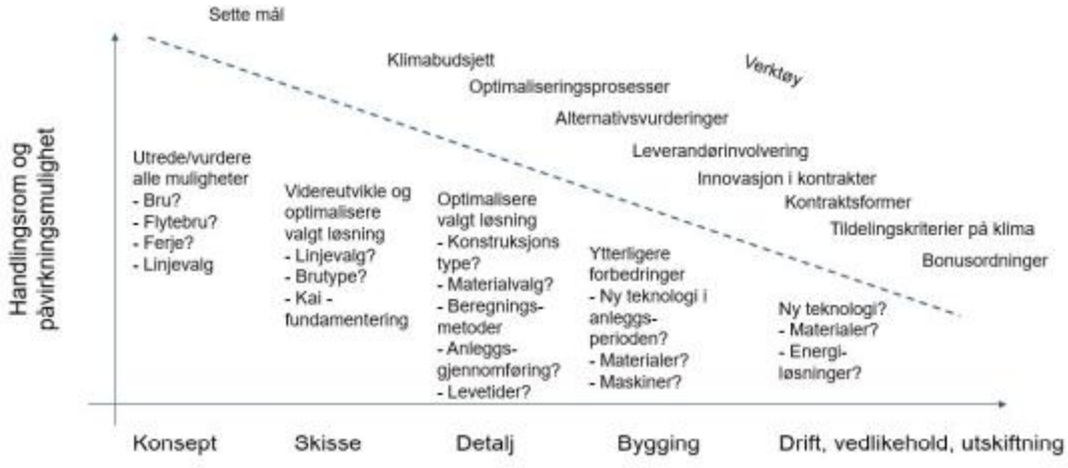


Figure 27: Decision impact during projecting phase55]

5.1 Prefab elements

The same report by SVV [55] studied the implementation of prefabricated concrete elements for bridges from 5 to 200 meters built in the period 2000-2017. 80% of the bridges are made of concrete with a majority of situ concrete bridges. Prefabricated elements are often used when cost, progress plan, location and challenges to set up formwork are the main decision factors.

High amount of fly ash in the concrete to achieve low carbon class A is normally no possible. This is due to requirements such as early firmness, hydration time and gravel with maximum corn size D_{max} [55].

The concrete recipe is also often standardized based on previous knowledge and casting cycles on at the manufacturing site. By changing the concrete mix, the overall cost for the project would increase.

The cross section of prefabricated elements is also more optimized compared to in situ concrete structures, therefore there will be material reduction by using prefabricated elements as shown in figure 28. The figure shows an example of material reduction for a bridge deck cross section between in situ cast bridge deck and prefabricated concrete beams.

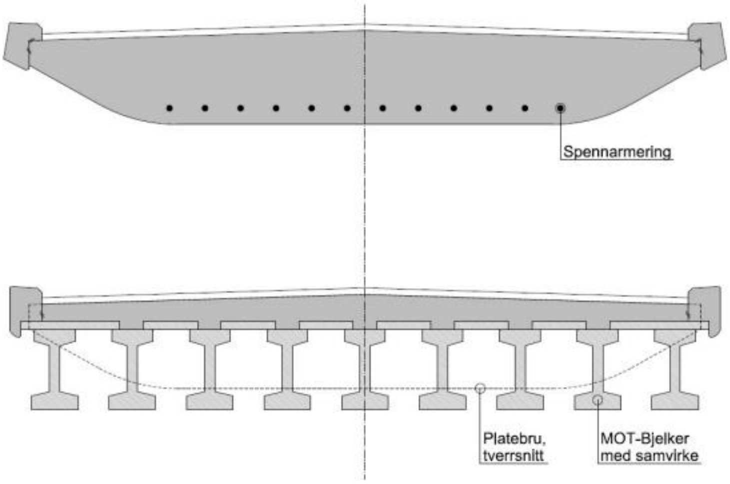


Figure 28: Cross section of in situ bridge and prefabricated beam bridge [55]

5.2 Construction optimizing

After the bridge concept has been chosen there is still room for reduction of emissions. For big bridges with long spans there is also necessary to optimize the construction in order to reduce the cost. This is not the case for smaller bridges, there are other parameters more important than material reduction [55].

In the pre project phase, the engineers, in collaboration with the architects, must determine the bridge decks cross-section. The aesthetics are determined by *clean lines and surfaces* and light conditions for the pedestrians below the bridge. The aesthetics must be chosen by considering the location and how important the aesthetics is for the nearby site.

Figure 29 shows two bridge deck where one is with rounded underside. These types of cross sections are less effective based on the material consumption compared to the right figure below. A non-optimal construction might lead to a disadvantageous post tension cables placement. By increasing the cross-section height to gain a greater moment capacity, one will get more material and increase self-loads. This will also happen for rounded underside since the extra material will not contribute as much as it will cause a bigger self-load.

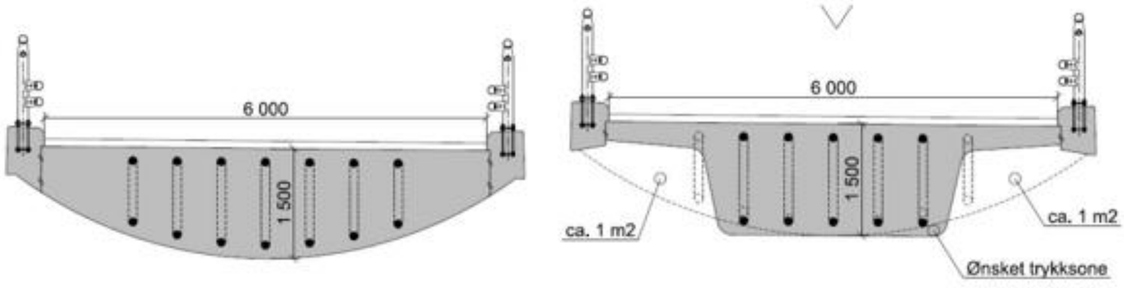


Figure 29: Right) Rounded underside. Left) Box girder underside [55]

For the cross sections above with those dimensions, by choosing the bridge deck to the right, one will get a concrete reduction of $2m^3/m$ which corresponds to a self-weight of $50\ kN/m$. For a long span bridge, these amounts of material reduction have a great impact on the overall emission for the bridge. An advantage with rounder underside is less surface and corners. This means lower risk for cracks and better durability. Another advantage is less rebars needed.

When it comes to large bridges like suspensions bridge, cable- stay bridges and cantilever bridges, the bridge deck is optimized based on other criteria such as foundations, challenges to span lengths and construction implementation.

5.3 Weight reductional cross section

Since bridges with rounded underside consume unnecessary material which doesn't contribute to the structural properties, they are considered uneconomical. The increase of concrete will also lead to other disadvantages such as heavier bridge decks which in turn mean more reinforcement, more formwork and longer building time. All of this gives a higher overall emission [55].

A possible solution would be to design the cross section with bubble decks or similar solutions. The Handbook N400 *Bruprosjektering* section 7.9.1 gives some guidelines and requirements on how to design the bubble decks, so they do not affect the durability and casting properties for the concrete. These solutions are frequently used in buildings, but not in bridges.

Figure 30 shows how a rounded underside bridge deck cross section could be designed more weight reductional.

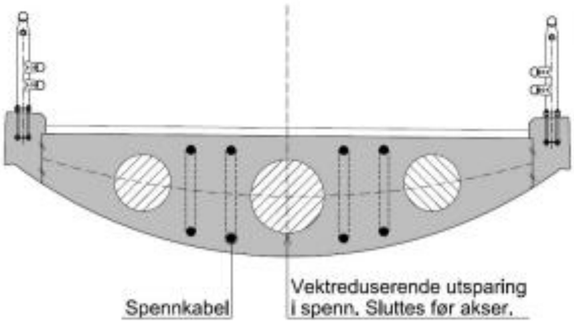


Figure 30: Weight reductional cross-section [55]

5.4 Concrete casting

If there is tight space between the rebars then it can be difficult to cast the concrete properly, especially around shear reinforcement and around the anchorage for post tensions tendons. An easy way to solve this would be to use a different concrete with reduced gravel, higher slump, and smaller stones. These measurements will lead to higher emission due to the increase of cement [55].

5.5 Formwork and building method

The building method can impact the overall emissions if measurements need to be taken account for such as longer curing time, need for heating and progress plan [55].
Formwork and building methods are normally the contractor's choice, but are mainly based on:

- Available equipment
- The building site location and availability
- If it is necessary for support constructions during the construction period

5.6 Service life

According to handbook *N400 Bruprosjektering* [31] the service life for bridges shall be 100 years. The definition for service life according to the report *Bærekraftige betongkonstruksjoner* goes as follows:

> *"The period a construction or parts of it, with scheduled service and maintenance, can be used without the need of extensive reparations"* [55]

Although a reduction of the service life from 70 years to 50 years could theoretically lower the overall emissions since it would require less concrete cover for the reinforcement, it would from an operational and maintenance view not be an option.

5.7 Service life extension and reuse

Reuse of constructions materials can give significant emissions savings. By crushing all the concrete from existing structures and letting the concrete react with air in a chemical process called calcium carbonate, approximately 20-25% of the CO_2 emissions can be reversed [55].

Projecting structures with reused components can be complicated and costly. The remaining capacity of the materials need to be calculated and controlled. If the structure is old, then there can be missing blueprints and information from the time the structure was projected. Therefore, assumptions need to be conservative which would cause an ineffective remaining capacity. Based on experience, Norconsult and Statens Vegvesen says there might be saving on emission by reuse materials, but not significant cost saving compared to building with new materials [55].

By reusing existing components, it is necessary to do a total overview of some relevant factors:

- Cost for the project
- Operational stage and maintenance
- Technical challenges by combining old and new components and structural parts
- Compromise in solutions
- Rest service life in old components
- Phase plans and construction time

For a 100-year time period it is not easy to conclude reuse would be an advantage. In some projects it might be more sustainable, but the cost for the project, future service and maintenance plan and non-optimal solutions would give bad cost benefit value [55].

5.8 Recycling of materials

In many road projects there are possibilities to recycle materials such as concrete, asphalt, surplus materials and more. The quality requirements for the recycled materials are high, which could limit the reuse potential [55].

In projects it should always be taken into consideration to use recycled materials. Crushed concrete can be used as aggregates in new concrete.
If the projects require an existing structure to be demolished, then reinforcement and steel components be sorted and delivered to recycle factories where it can be melted and reused [55].

5.9 Material choice

For big and massive construction there are just a few materials which stands for the major emission from. Previous emission calculations show that the materials who are the major contributors are concrete, steel, reinforcement and transportation. In addition will other scenarios like bad ground conditions and remote building sites affect the total emissions [55].

5.9.1 Concrete

To reduce the carbon footprint of concrete a natural solution would be to implement low carbon concrete as standard in the pre-project phase.
Handbook R762 *Prosesskode 2* [29] gives the rules for concrete in road applications. The handbook defines three durability classes:

- **SVV- Standard**: Parts of the construction where the exposure conditions and function requirements don't require any of the following concrete given below

- **SVV- Chemical**: Construction parts which are exposed for chemical attacks from groundwater in the soil and bedrock.

- **SVV- Low heat**: Constructions parts where the risk of restraining cracks from harden heating and temperature difference are significant which will cause a risk for its structural integrity.

Table 15 shows the values for air content, effective cement mass, mass ratio, fly ash and silica dust for SVV- concrete mentioned in handbook *Prosesskode 2* [29].

Table 15: The values for air content, effective cement mass, mass ratio, fly ash and silica dust for SVV- concrete mentioned in handbook Prosesskode 2 [29]

Concrete attributes	Concrete compound		
	SV- Standard	SV- Chemical	SV- Low heat
Air content fresh concrete for concrete quality up to B45	3 – 6 %	3 – 6 %	3 – 6 %
Air content fresh concrete for concrete quality better than B45	2 – 5 %	2 – 5 %	
Least effective cement mass	350 kg/m^3	350 kg/m^3	310 kg/m^3
Biggest mass ratio	0,4	0,4	0,45
Fly ash	14 – 30 %	14 – 25 %	max 40 %
Silica dust	3 – 5 %	8 – 11 %	3 – 5 %

SVV- Standard and Chemical shall satisfy the durability which are according to durability class MF40 while SV- Low heat need to satisfy the requirements according to durability class MF45. It is permissible to vary the amount of fly ash and silica dust within the limit value.

5.9.1.1 Reduce cement

By reducing the amount of cement in the concrete will give a better climate footprint but will give concrete with lower consistency. This can be challenge full for structures with high amount of rebars, anchorage zones for post tension tendons and thin and slender columns [55].

Low carbon concrete class A or better have a slower strength development than ordinary concrete. This might impact the progress of the project since the formwork for each casting session needs to stay longer before the next casting session can begin. The time before the concrete can be exposed for loading needs to be postponed [55].

5.9.1.2 Future development of sustainable concrete

Fly ash and silica dust are biproducts from industry with high emissions. Since only the main material is accountable for the carbon footprint, the emissions fly ash and silica dust are neglected. This opens for political discussion. A more realistic approach would be to transfer some of the emissions from the main product to the biproducts. This will have a big impact on the calculation the concretes emissions.

Since the consumption of fly ash as replacements for cement in concrete is increasing, it can lead to a shortage of fly ash with good enough quality. This will have big consequences for concretes EPD in the future [55].

There are several research on how to make concrete more sustainable. Some of the solutions are development of other cement types, replacement of cement in concrete and CO_2 capture.

5.9.2 Steel

Steel as rebars in combination with concrete gives a solid and versatile building material. Therefore, the amount of steel is proportional to the concrete.
The reinforcement in concrete can either be rebars, steel tendons or a combination. The emissions for the reinforcement are either rebars or tendons, or the steel quality is almost the same. There might be some differences in carbon content, alloys, manufacturing method and product treatments, but the major emissions come from the production of steel [55].

5.9.2.1 Recycled steel

The emissions from manufacturing of reinforcement, steel components, steel pipes and other steel parts are very dependent on the amount of extraction of steel from steel ore. Crushing, transportation, and processing of steel ore are very energy intensive. In the process of reduction from steel ore to pure steel there is used coal.
If the steel product is based on recycled steel from scrap, then the emissions will be significantly reduced [55].
Since the amount of steel consumption exceeds the access of steel scrap, then it can be augmented that if a region becomes more sustainable by using high amount of recycled steel, then other parts of the world need to mine more steel ore to satisfy their needs.
If recycling of steel after its service life becomes a requirement, then it will be economically attractive to recycle steel into scrap, which in turn the amount of scrap increases globally. This will drive the steel industry into a more environmentally friendly path.

Table 16 shows the emissions factor from steel manufacturing according to the report [55].

Table 16: Emissions factor from steel manufacturing [55]

Quality	CO_2 emission in kg from manufacturing 1 kg steel
Industry standard with no requirements	2,0
Minimum 70 % scrap	1,5
Minimum 90 % scrap	1,0
Minimum 99 % scrap	0,5

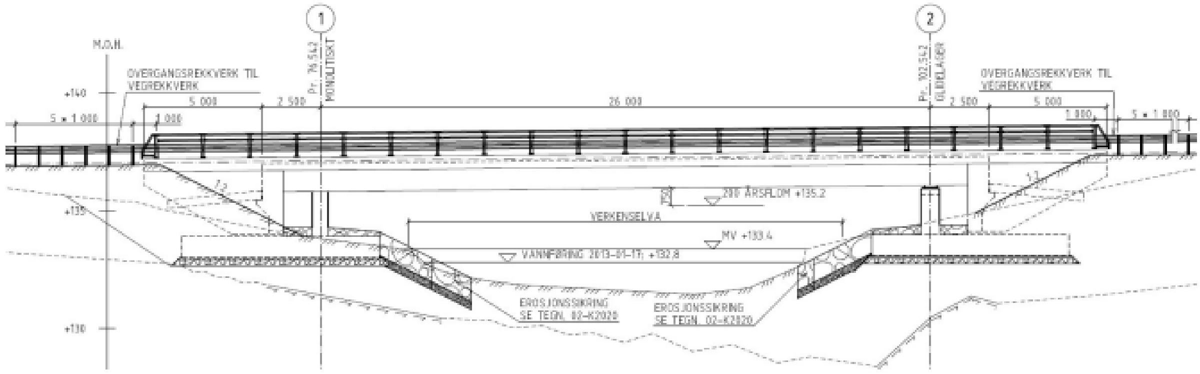
5.9.2.2 Reinforcement alternatives

Several alternatives to steel reinforcement are being developed. Some of the alternatives which are applicable at the market are rebars made of glass fiber, plastic fiber, basalt fiber and other mineral based reinforcement products. These products are used on special occasions. Some of the advantages with non-steel rebars is less concrete cover since these materials don't corrode which will give a lighter structure. The emissions of manufacturing these materials can be either higher or lower than steel, but the lighter structure requires less reinforcement. Since the materials don't corrode, then the service life can be extended which can give a significant effect on the overall emissions [55].

5.10 Effect of modern materials

In the report [55], a calculation of the emissions for a bridge has been made based of emission factors from 1990 compared to modern day emission factors.

The bridge is an in situ cast pre- tension beam bridge. The dimensions and cross section for the bridge is shown in figure 31.



Figur 2-13 Lengdesnitt, alternativ 1 (plasstøpt bjelkebru)

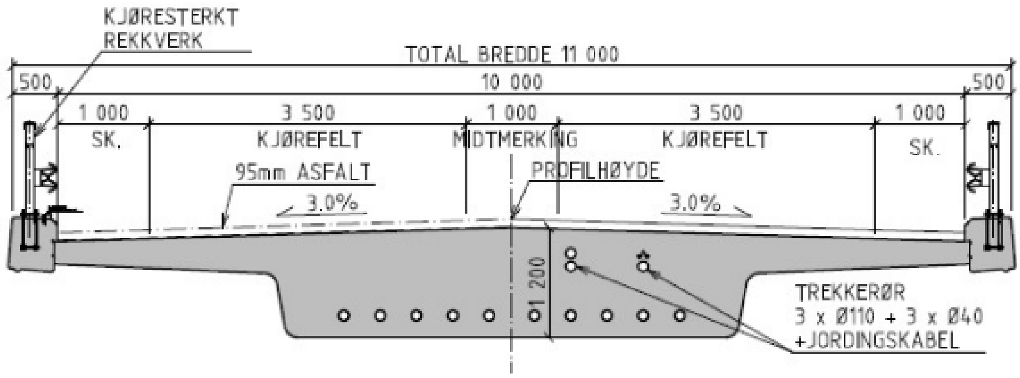


Figure 31:Global dimension and cross-section [55]

The emissions from the major materials in the bridge, the concrete, steel, and asphalt with material factors from 1990 is calculated to 678 CO_2- equivalents over 100 years period. If the bridge is designed with material factors from 2015, the emissions will be reduced by 43 % to 384 CO_2- equivalents. If the assumptions I based on the best materials factors, then the emissions can be reduced further to 70 % with an emission to 202 CO_2- equivalents. These material factors are for concrete, steel and asphalt and do not include construction work, mass transport, foundations, and other materials, which can be considered to have not been significantly reduced [55].

The material which has the biggest emission reduction is steel. The material factor for steel in 1990 is assumed to be $5\ kg\ CO_2 - eqv/kg\ steel$. This assumption can be difficult to validate, but the emissions for steel ore extraction varies from $3 - 7\ kg\ CO_2 - eqv/kg\ steel$. If the steel material factors from 1990 is set to the lowest assumption, then the emissions are 27 % lower than the baseline assumption, while for the highest steel material factor in 1990, the emission is 27 % higher than what have been assumed [55]. Figure 32 shows the effect of modern material factors [55].

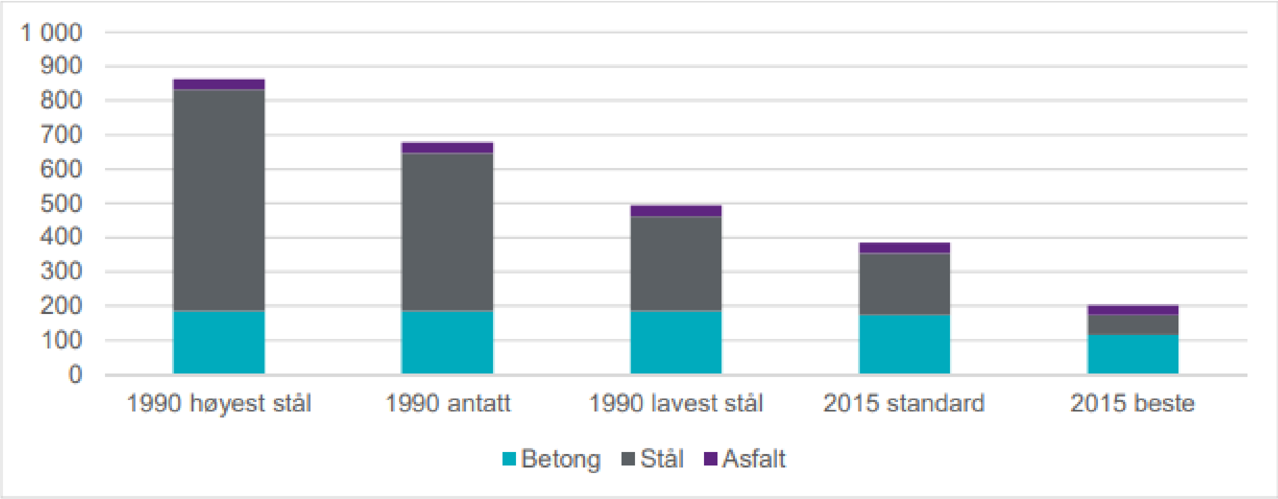


Figure 32: Effect of modern materials [55]

5.11 Evaluation of cost-effectiveness

Projects which need to satisfy emission reductions will benefit by rating the measurements in order of their cost effectiveness. The main scope for the measurements needs to be the most reduction at lowest price range. Measurements which would reduce the emission a lot would not necessarily be socially beneficial. In some cases, politicians could override such cost effectiveness assessments, but in the majority the measurements should be based on a socio-economic perspective [55].

To evaluate if a single measurement is economically beneficial, one must put it into context for the whole project with criteria as:

- Cost for one ton saved CO_2
- The total cost of the various measurements for emission reduction for the whole project
- Social benefits effects
- Market and industry benefits effect

If new technology has the effect of leading the industry to become more sustainable, then it can be argued to be implemented even if the cost is high. An example could be to demand zero emission constructions site where all the equipment and machines are driven by electricity. If the public sector specifies such requirements in their projects, then over time the whole industry will be more sustainable since the machines will be more commercial.

Climate measurements with a negative cost should be acceptable as long as it will not require huge investigation whereas the measurements will impact progress and security [55].

Some costs will also occur in the future, like rehab, operational measures and maintenance. These costs should be included in the calculations with the help of an LCC analysis. The project's costs should be divided into two categories, price and cost. Price in the sum which owner of the structure needs to pay to construct the structure while cost is the society's total economic, environmental and other non- priced effects cost in a long- term period [55].

5.11.1 Cost of emission savings

The Norwegian environmental directorate operates with three categories for the cost of emission saving per ton CO_2 [55]:

- $Low\ cost: < 500\ kr/ton\ CO_2$

- $Medium\ cost:\ 500 - 1500\ kr/ton\ CO_2$

- $High\ cost: > 1500\ kr/ton\ CO_2$

A benchmark for the industry should be an average cost with a price of $1000\ kr/ton\ CO_2$. The KraKK- project by the Norwegian road authority shows there is a connection between the project price and emissions. Based on several projects in NTP, it is assumed that a project has an emission of $35\ ton\ CO_2$ for each million kroner spent. For bridges, Norconsult operates with $50\ ton\ CO_2$ per million kroners [55].

5.12 Recommendations

Based on the work in the report *Bærekraftige betongkonstruksjoner* [55], Norconsult has some recommendations on how concrete structures could become more sustainable:

Objective and plan phase:

- Objective: The objective to reduce the emission for the projects should be a criterion as important as cost and progress plan

- Involvement in early stage: The effect of reduction of emission for a concrete structure is higher when it is done at the early stage. Choosing routes, construction types, placement and zoning plans are normally done at early stages, and this is where a significant amount of emission can be saved. Further in the projecting and construction plan stage, choice of materials and optimization can additionally reduce the emissions.

Materials and construction types:

- Emission calculations: Identify which materials have major impacts on the emission calculations for the structure. Generally concrete, steel, asphalt and transportation are the factors that significantly contribute to high emissions.

- Comprehensive planning: A well projected solution will give the lowest emissions based on quality and service lifetime. By putting more work in the projecting phase one will be able to lower a significant amount of the emissions. Advanced calculations instead of the rules given in the Eurocodes and standards, as long they satisfy the requirements, can save huge portions of materials.

- Comprehensive assessment: The construction functions and emissions must be analyzed as a whole system. If parts of the structures are analyzed isolated, it might lead to a higher emission at another post or stage.

- Use of prefabricated elements: By using prefabricated elements the structure can be built in a shorter time period. The installation will therefore be more effective and reduce the emissions. Nevertheless, the emission by using prefabricated elements should be in context of the whole service life and not exclusively for installation phase.

- Use of different concrete quality: For big structures where the amount of concrete is huge it can be environmentally beneficial with different concrete qualities. If the needs for strength, casting properties and progress is known, then concrete with lower emission can be applied for construction parts where these criteria are not important.

- Standardized material choice: Sine huge portion of the emission comes concrete, steel and asphalt, the suppliers have researched and developed more sustainable solutions. By using materials with lower emissions there is almost no or small additional cost. It should therefore be requirements to choose the material with the lowest emissions.

- Use of recycled materials and reuse of components: Many projects include demolition of an existing structure. It should be evaluated if any of the components can be reused in the new structure or on other projects. The project should also strive to use recycled materials and deliver the demolished materials to recycling.

Documentation and tools:

- Tools and guidelines: It should be developed tools for the pre project phase which can calculate the emissions for the whole projects at each stage. This way new materials, solutions and technology can be easier to accept and to be used. This will also give fast and good advice and guidelines to the different parties who are involved in the project.

- Evaluate the cost- effectiveness: The principle of cost- effectiveness should be implemented in the decision-making process. Three measures should be evaluated:

    - Evaluate the emissions in the choice of construction type and placements at early stage
    - Choose environmentally materials, especially low carbon concrete and recycled steel
    - Put in more work at the pre- project stage and use of more advanced calculations methods in order to reduce material consumption and workload at the construction site

6 Reducing carbon footprint for bridge structures

6.1. High-performance concrete bridges

Although concrete is a long-lasting material in comparison to other building materials, it is susceptible to degrading mechanisms such as carbonation and chloride penetration, which cause the reinforcement bars to corrode and shorten the service life. This demands extra caution, particularly in chloride-rich environments such as coastal areas and where salt is used to melt ice in the winter [56].

The Norwegian government has chosen to invest in several important national highways in order to bring them up to modern standards [57]. To handle the harsh Norwegian weather while also reaching the ambitious climate targets set out in the Paris Agreement, developing these major infrastructures demands innovative and clever solutions. Using ultra high-performance concrete (UHPC) to reduce the amount of concrete required in a construction could be one solution. This type of concrete is known for its exceptional strength, durability, and ductility [58].

Concrete structures' bearing capacity is typically limited by the dead load, especially in structures with long spans. UHPC's improved mechanical strength allows the construction of slimmer and lighter structures [59]. Furthermore, because UHPC is exceptionally durable and does not require repair during service life, it is particularly well suited to bridge building in tough environments [60].

6.1.1. HPC and UHPC compared to regular concrete in bridges

To moderate global warming and avoid uncontrolled climate change, the Intergovernmental Panel on Climate Change (IPCC) proposes that industrialized countries reduce their CO_2 emissions by a factor of four or five [61]. A solution is to improve the concrete performance which lowers the amount of concrete required for a given construction procedure. Increased mechanical strength will also increase the CO_2 emissions per cubic meter of concrete produced but reduce the amount of concrete required to construct a specific structural component [62]

Habert, G et. Al [62] conducted a study which evaluates the environmental consequences for a bridge made of high-performance concrete (HPC) compared to regular concrete with the help of LCA study based on the standard ISO 14010. The LCA study's goal is to determine which of the two bridge designs has the lowest effect on the environment while still providing the same performance. The normal concrete bridge is in Saône et Loire, while the UHPC bridge is in Bourges. Both bridges are in France.

Figure 33 and 34 shows the global and cross-sectional dimensions for both bridges.

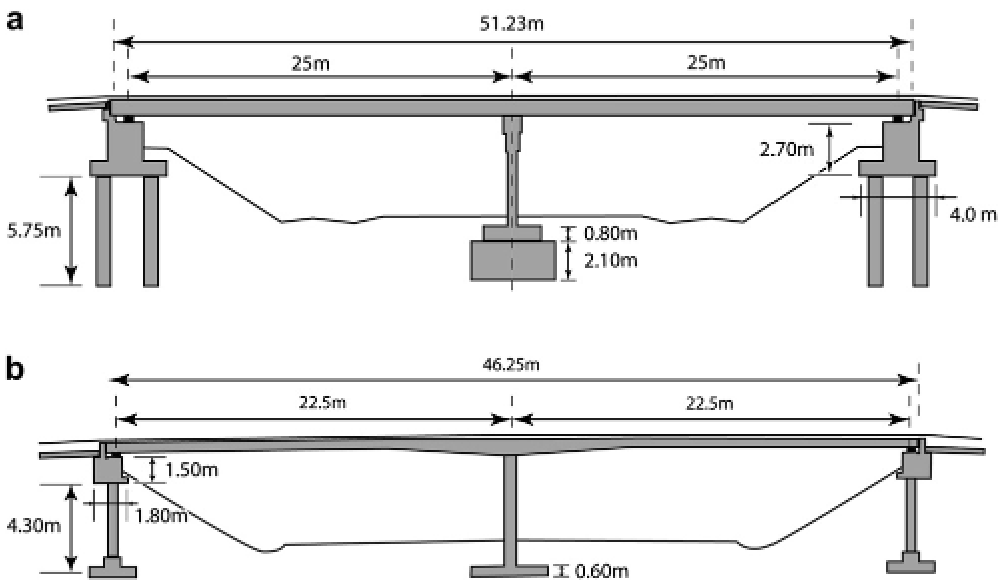


Figure 33: A) Bridge built with normal concrete, B) Bridge with UHPC [62]

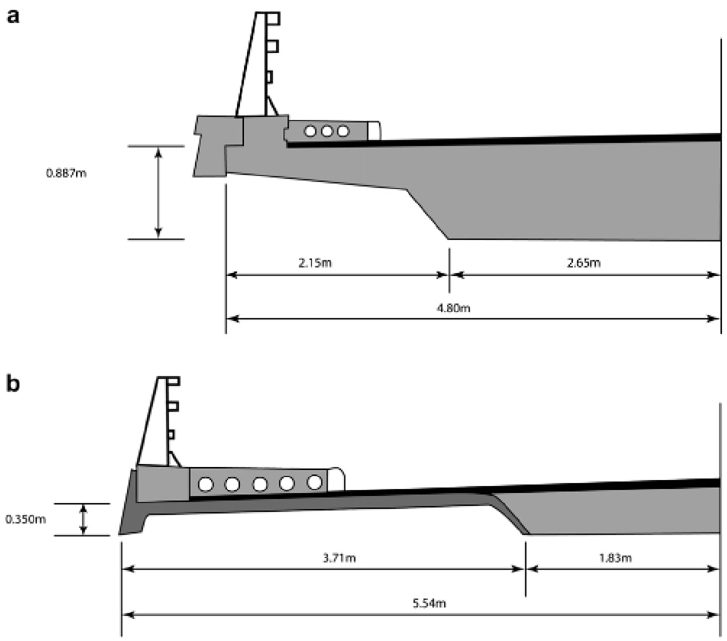


Figure 34: A) Cross section of normal concrete bridge, B) Cross section of UHPC bridge [62]

Because the two bridges do not have the same measurements, comparing them may be challenging. They are, however, primarily traditional bridges designed to cross a four-lane highway with a two-lane road bridge deck [62]

Technical data and concrete mix for both bridges are given respectively in table 17 and 18.

Table 17: Technical data for the LCA study for both bridges [62]

	Traditional concrete bridge			High performance concrete bridge		
	Type	Qty	Unit	Type	Qty	Unit
Structural materials						
	Low strength concrete	37	m^3	Low strength concrete	IDEM	
	Foundation concrete	143	m^3	Foundation concrete	28.4	m^3
	Deck concrete	411	m^3	C80 concrete	65	m^3
				C60 precast concrete	119	m^3
	Pylon concrete	251	m^3	Pylon concrete	64	m^3
	Cables at plant	14.2	t	Cables at plant	7.3	t
	Reinforcing steel	60.2	t	Reinforcing steel	40	t
	Cement grout (CEM I)	5.1	t	Cement grout	IDEM	
	Conducts	1000	m	Conducts	IDEM	
Equipments						
	Bitumen sealing	490	m^2	Bitumen sealing	IDEM	
	Pavement	70	t	Pavement	IDEM	
	Asphalt	34	t	Asphalt	IDEM	
	Precast concrete	22.75	m^3	Precast concrete	IDEM	
	Vehicle parapet	136	m	Vehicle parapet	IDEM	
	Canalisations (Extruded PVC; 1.5 kg m^{-1})	500	m	Canalisations	IDEM	
Transport						
	Transport site work machine	4770	km	Transport site work machine	IDEM	
	Transport equipment from regional storage	4.75	t km	Transport equipment from regional storage	IDEM	
	Transport concrete from ready mix plant to site work	842	m^3	Transport concrete from ready mix plant to site work	157	m^3
	Transport reinforcing steel	60.2	t	Transport reinforcing steel	40	t
	Transport prestressed steel	14.2	t	Transport prestressed steel	7.3	t
				Transport precasting plant to site work	119	m^3
Construction						
Site work facilities	Tap water	30,000	L	Site work facilities	IDEM	
	Electricity medium volt	10,000	kWh			
	Bungalows transport	500	km			
	Bungalows	5				
Use site work machine	Diesel (included diesel for the diesel electric generator)	22,000	L	Use site work machine	IDEM	
				Crane for precaste HPC; 8 h, 6 days	24.5	MJ
				Pump; 6.19 MJ m^{-3}	402	MJ
Workers transport	Operation Van	32,600	km	Workers transport	IDEM	
	Operation passenger car	57,800	km			
Maintenance						
Survey	Operation Van<3.5 t	1100	km	Survey	IDEM	
	Diesel	930	L			
Regular maintenance	Operation Van<3.5 t	2040	km	Regular maintenance	IDEM	
	Operation lorry, full	640	km			
	Diesel	4800	L			
Repair materials	appareil d'appui	1	p	Repair materials	IDEM	
	Bitumen sealing	980	m^2			
	Pavement	490	t			
	Asphalt	16	t			
	Precast concrete (curb)	40.8	m^3			
	Vehicle parapet	104	m			
	Repair mortar	6.6	m^3			
	Painting	600	kg			
Repair transport	Operation Van	7250	km	Repair transport	IDEM	
	Operation lorry, full	3700	km			
	Diesel	26,880	L			
End of life						
Deconstruction	Diesel	4000	L	Deconstruction	IDEM	
	Particulate (cf disposal building concrete)					
Crushing	Diesel	3000	L	Crushing	IDEM	
Transport to landfill	Transport lorry 32 t	1170	t	Transport to landfill	485	t
Landfill	Disposal concrete to inert material landfill	1050	t	Disposal of concrete	392	t
	Disposal bitumen to sanitary landfill	55	t	Disposal of bitumen	55	t
	Disposal steel to inert material landfill	59.5	t	Disposal of steel	38	t

Table 18: Concrete mix for both bridges [62]

Concrete type	Unit	Cement	Limestone filler	Admixture	Water	Sand	Round gravel	Crushed gravel	Bitumen	Heating
Low strength concrete	m^3	225	75	1.66	150	740	380	690		
Foundation concrete	m^3	385		2.7	185	740	380	690		
Deck concrete	m^3	290	125	2.9	170	660	300	760		
Pylon concrete	m^3	420		2.9	155	650	400	615		
C60 precast concrete	m^3	450		6.75	177	810	910			250 kWh
C80 concrete	m^3	425		9	133	790	1050			
Repair mortar	m^3	380				2380				
Precast concrete	m^3	190	60	1.66	125	740	380	690		250 kWh
Pavement	t						944		55.4	
Bitumen sealing	m^2		4.89					69.88	4.98	17.35 MJ
Sheet asphalt	kg		0.26			0.66			0.08	

Abiotic depletion, acidification, eutrophication, global warming, and ozone layer depletion are the five environmental impacts of the different phases of each bridge solution which have been analyzed. The relative impacts of the two bridge solutions on the different phases of the life cycle are presented for each indicator. It is noticeable that two phases contribute mostly to the environmental impacts: material production and bridge maintenance. The construction phase is also critical, but the transportation and end-of-life phases are insignificant. The results are shown in figure 35.

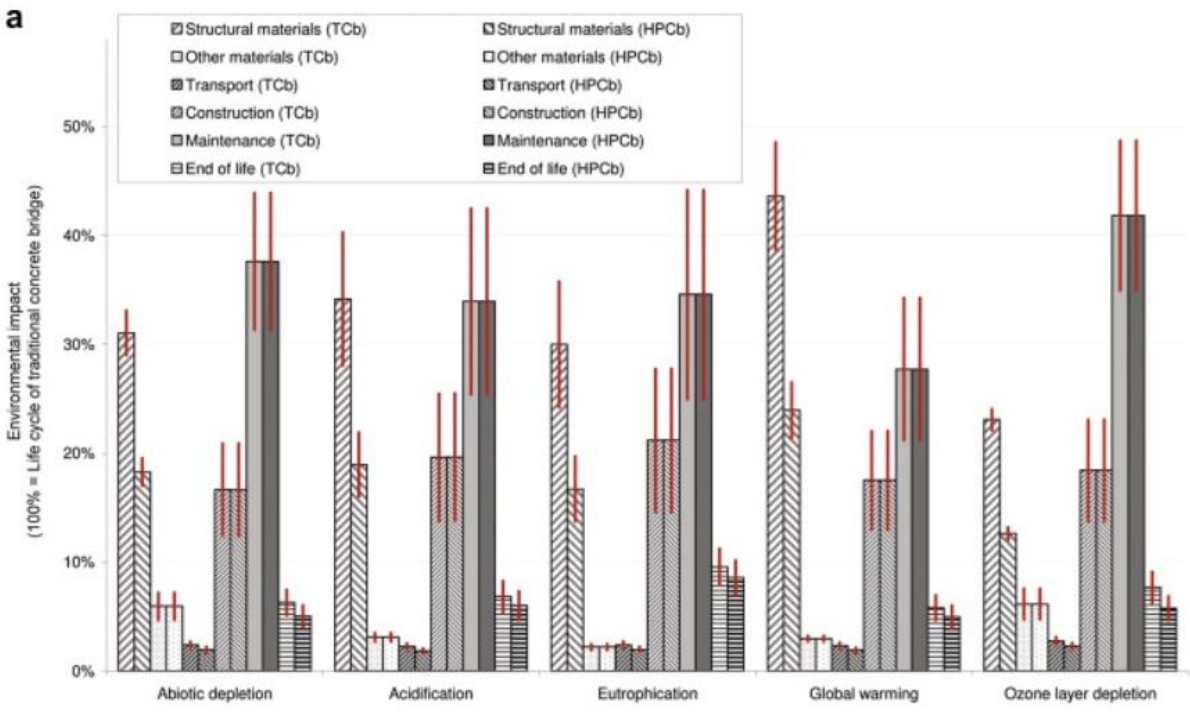


Figure 35: Environmental impacts from traditional concrete bridge (TCb) and high-performance concrete bridge (HPCb) at several life cycle phases [62]

The two solutions show similar tendencies, with the exception that the high-performance bridge's material construction phase is far less significant. The remaining phases are identical perhaps because the same work is considered in the maintenance phase or because the additional work done by the precast solution is minor during the building phase, or even though there are differences, they are in phases that are not particularly significant, especially the transport and end-of-life phases.

Below are the environmental details of the structural material manufacturing process. Steel and concrete have similar effects on abiotic depletion.
Concrete is dominating for indicators of acidification, eutrophication, global warming, and ozone layer depletion, while steel is prominent in measures of ecotoxicity. For concrete parts, the influence from the concrete in the deck clearly dominates the conventional bridge while this is not the case for the high-performance bridge.

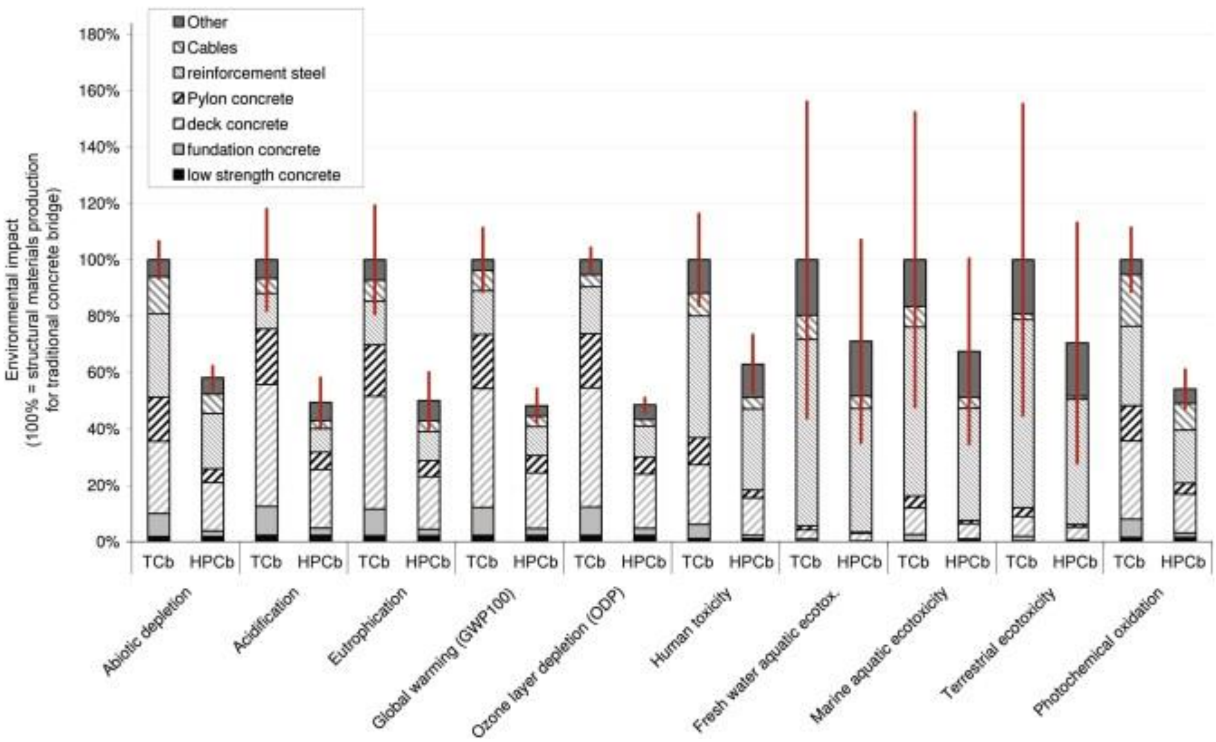


Figure 36: Environmental impacts of different structural elements [62]

Habert, G et. Al [62] evaluated the results by performing a Monte Carlo analysis. The results are shown in figure 37.
Except for global warming, the data reveals that there is no significant difference in the environmental impacts between the two bridge alternatives. This means that a high-performance concrete bridge will have a lower global warming impact on average than a normal concrete bridge. This applies to two randomly selected classic bridges in France constructed to cross a four-lane highway with a two-lane bridge deck. T F, the variation will be within 3 to 40%, depending on the different distance between the facilities and construction site, and the efficiency of the equipment and the material manufacturing plant.

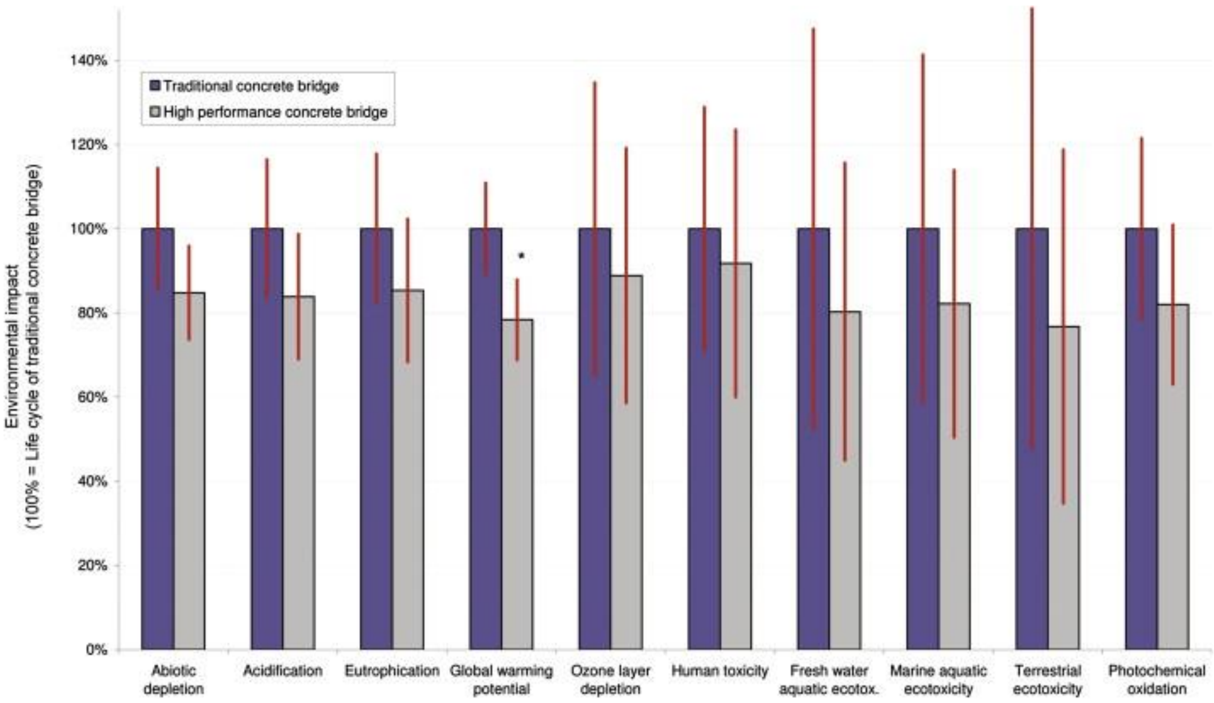


Figure 37: Comparison of the environmental impacts for normal and high-performance concrete bridges. The error bars are presented in red [62]

Another study conducted by Larsen, I, L et al [56] performed a comparative LCA analysis of a T-beam bridge structure developed with UHPC and normal strength concrete to see which has the lowest emissions profile. The purpose of the research was to demonstrate the impact of design and to see if UHPC is a good material for minimizing lifetime emissions for bearing concrete structures.

The bridge, which is a pedestrian bridge, spans over a four-lane motorway and is 40 meters in length and 3 meters in width. Figure 38 shows the bridge construction, which is divided into two 20-meter spans and consists of two simply supported T-beams. The location is assumed to be in southern Norway, along the new 4-lane motorway (E18) connecting Tvedestrand and Arendal. This place is very typical for the Scandinavian climate.

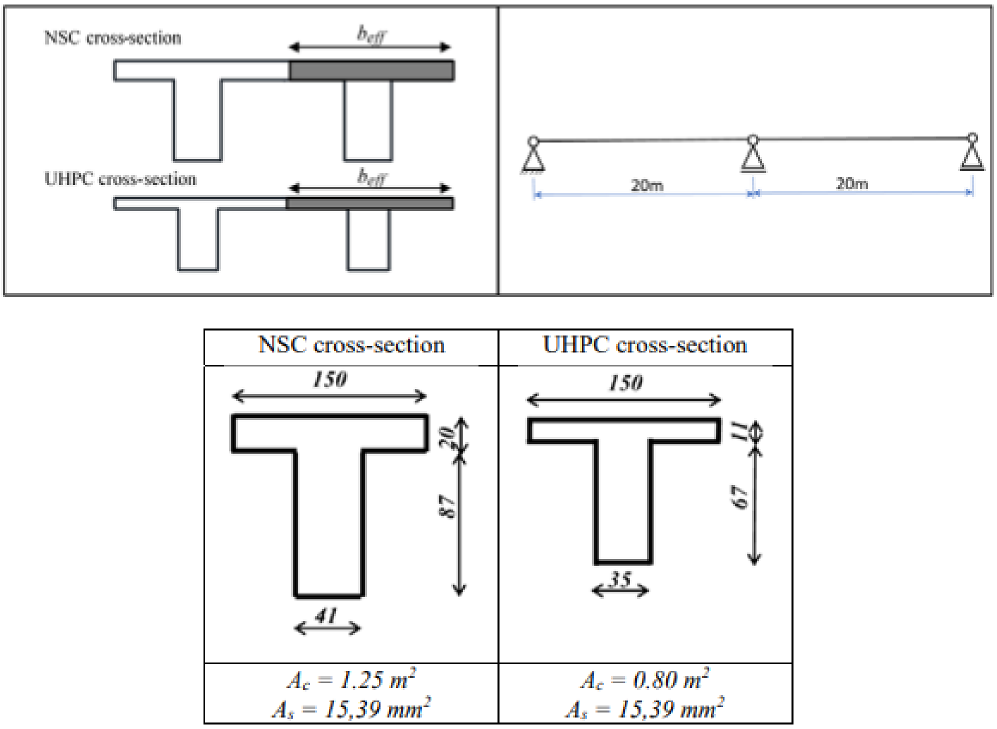


Figure 38: Pedestrian bridge constructed with T- beams [56]

The concrete mix properties and material consumption for both bridges are respectively given in the table 19 and 20.

Table 19: Concrete properties [56]

Concrete mix	MPa			‰			GPa	
	f_{ck}	f_{ctm}	f_{cd}	ε_{cu}	ε_{c1}	φ	E_{cm}	$E_{c,eff}$
Normal concrete	30	2,9	17	3,5	2,2	1,5	33	13,6
UHP concrete	150	9,0	85	3,5	2,2	0,8	50	27,8

Table 20: Material consumption [56]

Material	Normal concrete bridge	UHP concrete bridge	Unit
Concrete C30/C37	51	–	m^3
Concrete UHPC	–	32,30	m^3
Accelerator	–	0,97	*ton*
Portland cement	17,52	23	*ton*

$Gravel, round$	48,97	$-$	ton
$Plasticizer$	$-$	0,99	ton
$Sand$	43,81	32,95	ton
$Silica\ fume, recycled$	$-$	7,46	ton
$Silica\ sand$	$-$	6,82	ton
$Tap\ water$	10,55	4,32	ton
$Reinforcement$	9,81	9,72	ton
$Steel\ fiber$	$-$	5,04	ton
$Transport, 16-32\ t\ lorry$	1,28	38,82	$k-tkm$
$Transport, international\ tanker$	$-$	54,01	$k-tkm$

The cement content of UHPC is two to three times that of normal concrete. As a result, reducing the overall amount of concrete used in bridge building is critical for minimizing environmental effects [56]. Because UHPC is not produced in Norway for commercial usage, it is shipped from France to Norway.

The lifetime of UHPC is estimated to be at least two times longer than that of regular strength concrete. This is due to the mechanical strength and durability of UHPC allowing for a far longer lifetime than standard normal concrete bridges. This is important in order to determine environmental impact during the life cycle of both bridges. Bridges in Norway have a service life of 100 years, according to the Norwegian Public Road Authority. As a result, it was assumed that the UHPC bridge will last 200 years under the same conditions. Because of the huge uncertainties connected with destruction, recycling rate, energy use, and other factors after 200 years, the end-of-life phase was not assessed [56].

Over a 200-year lifespan, the UHPC mix had the lowest environmental impacts in all categories which ranged from 79-86 percent of the total emissions compared to regular concrete. For GWP, the UHPC had had an emission of 84% according to the results which are shown in figure 39.

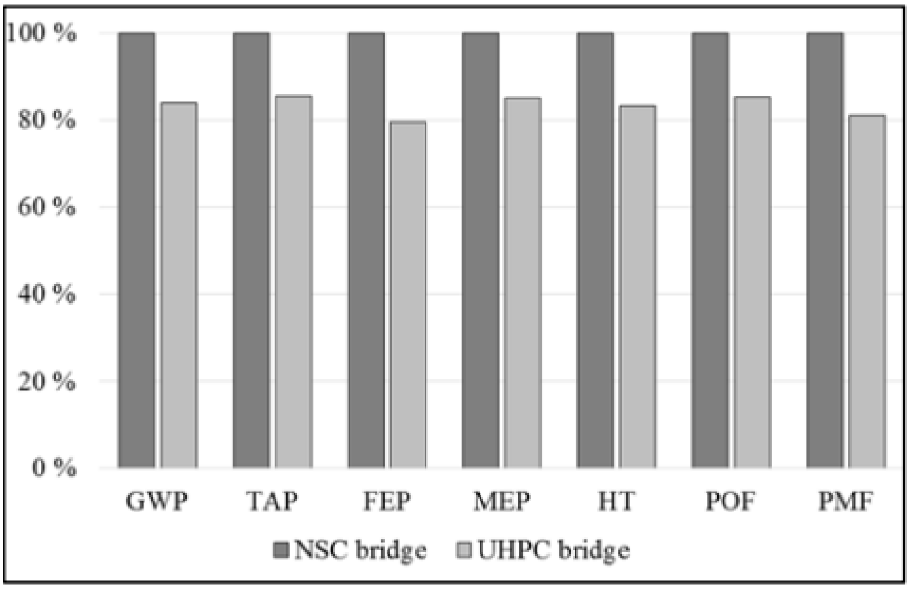


Figure 39: Life cycle assessment for normal strength concrete and UHPC 56]

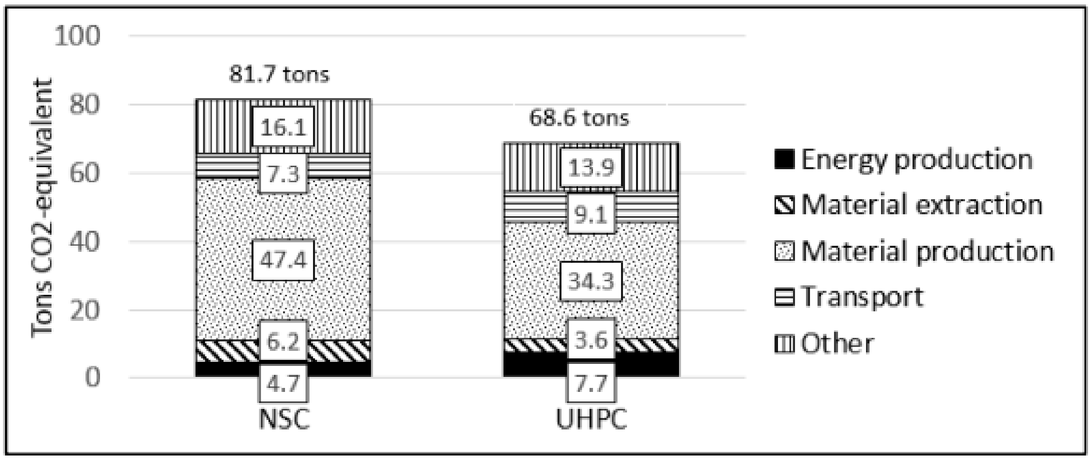


Figure 40: GWP for normal strength and UHPC [56]

When looking at GWP isolated, the normal concrete mix emits 81,7 $ton\ CO_2 - eqv$ over its lifespan, while the UHPC option emits 68,6 $ton\ CO_2 - eqv$. Material production accounts for the majority of CO_2 equivalent emissions in both options, accounting for 58 percent of total emissions in the normal concrete mix and 50 percent in the UHPC mix. Cement manufacturing, at 26,7 $ton\ CO_2 - eqv$, is the largest contributor to the emissions for the normal concrete alternative, followed by steel components at 12,4 $ton\ CO_2 - eqv$. Cement contributes with 17,7 $ton\ CO_2 - eqv$ of the emission for the UHPC option, while steel in UHPC bridge contributes with 9,4 $ton\ CO_2 - eqv$. The results are shown in figure 40.

6.2 Steel and high strength steel bridges

Steel is a key component in bridge building, which is why it is increasingly used in long, medium, and short span bridges, as well as railway bridges and even pedestrian bridges. Steel is noted for its adaptability, strength, and ductility, which enable bridges to successfully resist both static and dynamic loads [63].

Carbon steel, heat-treated carbon steel, stainless steel, and weathering steel are the most common types of steel used in bridges. The type of steel used in bridges is commonly determined by the bridge type. Corrosion and rust-resistant stainless steel and weathering steel bridges are appropriate for bridges built in acidic or alkaline environments. Bridges made of heat-treated carbon steel are also excellent because of their moldability, durability, and strength [63].

6.2.1 Steel bridge

The selection of materials and bridge types is a critical step in the bridge project, as it can have a major impact on the environmental performance of the entire life cycle. The reinforced concrete and steel composite material is used to construct the majority of bridges. Steel, as the most common bridge construction material, has a higher initial embodied energy and emissions than concrete. However, steel is a 100% recyclable material which can compete with concrete when it comes to emissions [64]

6.2.1.1 Randselva bridge

Multiconsult have made a report for a preliminary project for Randselva bridge where the bridge decks consist of composite deck [65]. Randselva bridge is constructed for dimension class H5 with two lanes and barrier in between. The dimensional annual day traffic throughout the year is 7740.

The area along the bridge is hilly with big height variations at both ends of the bridge. On the westside at Eggermoen the geotechnical report showed the ground consist of gravel for depth of 17,1 meters. Further down the ground consists of moraine, stones and gravel. At the depth of 35,7 meters there was no sign of bedrock.

On the eastside at Kleggerud, the geotechnical report showed the bedrock was at a depth of 17-18 meters. Based on the geotechnical report and terrain the major span for the bridge needs to be 125 meters.

Randselva bridge is constructed by a continuous steel- concrete composite girder bridge. The connection between the pillars and bridge deck is monolithic. Table 21 shows information about Randselva bridge.

Table 21: Information about Randselva bridge [65]

Geometri/funksjon	Beskrivelse
Funksjon	Bru for E16 over Randselva
Føringsbredde	12,5 m (1,5+3,5+0,75+1,0+0,75+3,5+1,5)
Fri høyde	Opptil ca. 55 m
Lengde og spenn	L = 540 m (125 + 30+40+30 + 110 + 25+30+25 + 125)
Horisontal kurvatur	R = 1050 m
Vertikal kurvatur	2,7 %
Tverrfall	6,3 %
Type bru	Stålkassebru
Max. konstruksjonshøyde overbyg.	5000 – 10000 mm
Søyletype	2 stk. V-formede støtter (brua sett i oppriss) består av rektangulære kassetverrsnitt i betong som søyler BxD = 7000 x 4000-7000mm (variabel) (t = 500 og 1000mm).
Fundamentering	Akse 1 fundamenteres på borede pilarer ø1200 i løsmasser. Akse 2 og 3 fundamenteres på borede pilarer ø1500 til berg. Akse 4 fundamenteres på ø200 stålkjernepeler til berg.

The bridge deck height is 5 meters except above the supports where there will be negative moments. At the pillars, the deck height increases to 10 meters. The cross-section, which is shown in figure 41, is diagonally braced inside. The steel plate thickness varies from 15-40 mm.

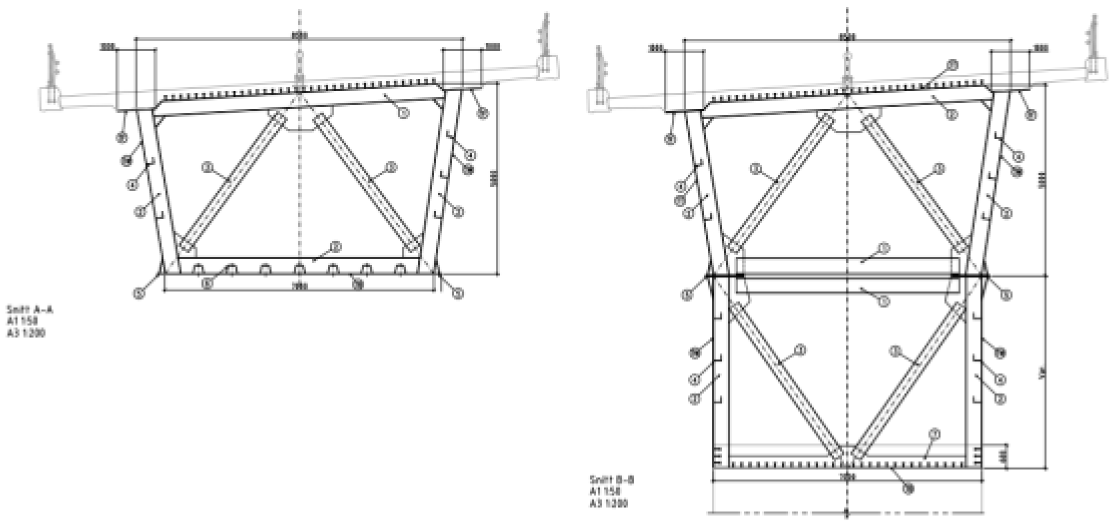


Figure 41: Cross section of Randselva bridge. Left shows the cross- section at mid span. Right is the cross-section at pillars [65]

The bridge is built by the incremental method where the bridge parts are assembled into steel girders with a height of 5 meters on the eastside at Kleggerud. The parts are welded together into sections of 110 meters spans. For the steel girder to be able to stay floating midair without ground supports, a tower is constructed, and cables are attached to the tip of the steel girder. The whole bridge is pushed 5 times at lengths of 100-110 meters.

Figure 42: Example of incremental method [65]

Du, G et al [64] performed a LCA comparison study for a concrete and a steel- hybrid bridge. The case study bridge is in Nacka, Sweden. Today's traffic volume of 57,000 vehicles per day is expected to increase to 85,000 per day in 2030.

In order to be able to handle the traffic volume increase the current bridge needs to be replaced. For the study, two bridge designs were presented. Both bridges need to fulfill the length spans of 373 m, with a width of 29,5 m and height of 30 m.

The cross section and dimensions of both designs are respectively shown in figure 43 and table 22.

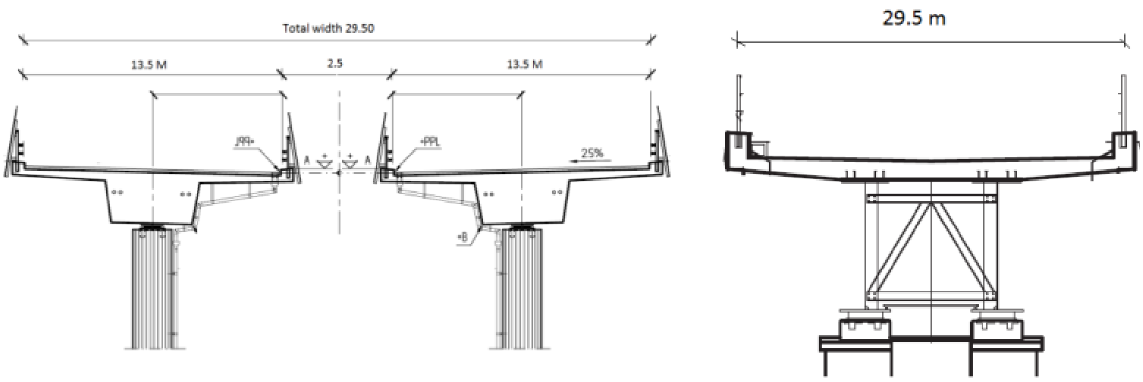


Figure 43: Cross section for the case study of Nacka bridge. Left) Concrete deck bridge, Right) I-girder steel hybrid bridge [64]

Table 22: Bridge dimensions [64]

Bridge specifications	unit	Reinforced concrete bridge	Steel I-girder bridge
Total bridge length	m	373	373
Total bridge width	m	29.5	29.5
Total bridge area	m^2	10257	11004
Steel painting area	m^2	--	2585
Paved area	m^2	9231	9903
Bearings number	set	12	20
Parapets length	m	1564	782
Edge beam length	m	1492	746

The concrete option consists of two 13.5-meter-wide parallel beam bridges separated by a 2.0-meter gap. On the bridge deck, 44-ton aluminum parapets have been built. The superstructure is prefabricated, with pre-tensioned tendons running along the length of the bridge. The entire cross section is made from a 1.7 m thick in- situ cast reinforced concrete slab. Seven circular reinforced concrete columns with a diameter of 1.4 m support the substructure.
The major load bearing component of the superstructure are two steel-I girder beams. The reinforced concrete deck has a thickness of 0.265 m. Eight square reinforced concrete columns support the entire superstructure. The steel I girder section, which serves as the major loading bearing components, varies in height from 1.13-2.02 m along the bridge and is galvanized and painted with epoxy to avoid corrosion. Every 4.5 meters, steel bracing is installed between the steel I girder beams to stabilize against lateral buckling.

The necessary material quantities for both bridge designs are given in table 23.

Table 23: Material quantities. Proposal 1) Concrete bridge, Proposal 2) Steel hybrid bridge [64]

Structural items	Unit	Proposal 1	Proposal 2	Type of material	LCI Database	Transportation distance
Concrete	m^3	14191	10863	Normal concrete & Concrete sole plate and foundation	Ecoinvent	60 km by truck
Reinforcement	ton	2563	1020	Reinforcing steel, at plant	World steel association and Ecoinvent	150 km by truck
Structural steel	ton	---	1055	Low alloyed steel, at plant	World steel association and Ecoinvent	400 km by ferry + 100 km by truck
Aluminium parapets	kg	43948	21974	Production mix of Aluminium at plant	Ecoinvent	100 km by truck
Bearing	kg	1236	2060	Stainless steel hot rolled coil	ELCD	----
Painting	m^2	---	2585	Zinc coating	Ecoinvent	----

Over a 100-year life span, the bridge bearings are changed twice, steel sections are repainted three times, the edge beam is replaced three times, and the parapets are replaced once, see table below. However, traffic load, periodic inspection, specified service life and budget plan all have an impact on realistic maintenance intervals. Instead of measuring the environmental benefit of recycling at the end of life, it is considered the steel contains an average of 37 percent secondary steel scrap at the material manufacturing phase. The maintenance stage for both bridges are shown in table 24.

Table 24: Maintenance stage [64]

Maintenance activities	Unit	Maintenance interval [years]	Proposal 1	Proposal 2
Bearing replacement	kg	40	1236	2060
Repainting of the steel	m^2	30	---	2585
Edge beam replacement	m^3	25	134	67
Parapet replacement	kg	50	43948	21974

The results, figure 44, shows that the initial material manufacturing is the most significant factor in each design option. When compared to the concrete bridge solution, the steel composite design has a better environmental performance based on the selected impact categories, which is 45 percent less in CED, 21 percent less in GWP, 19 percent less in ODP, 22 percent less in HP, 19 percent less in POFP, and 12 percent less in PMF. The key reason is that the steel composite bridge uses less material, even though raw steel fabrication has greater embodied environmental burdens than standard concrete, since it doesn’t require reinforcement. This results in a 37 percent deduction in environmental emissions for the steel composite bridge design.

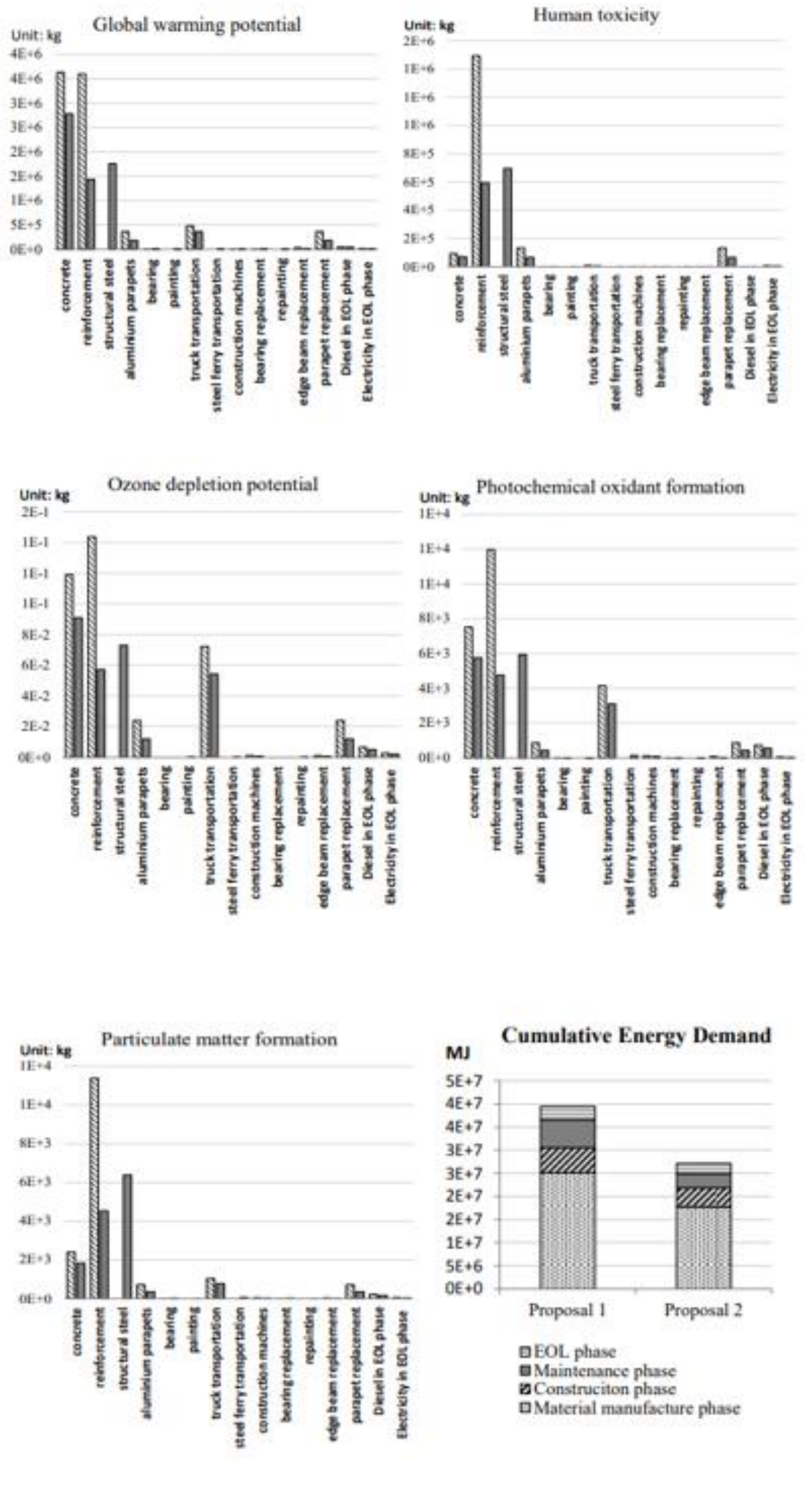


Figure 44: Life cycle assessment results [64]

Steel allows for a slender and thinner deck to be created, as well as full recycling capabilities. The steel bridge alternative has a superior environmental profile in various categories than the concrete bridge.

6.2.2 High strength steel bridges

High-strength steel (HSS) refers to high-performance structural steels with a greater yield strength than 355MPa [66]. Normalizing, quenching, tempering, and thermomechanical controlled rolling are the most typical processes for generating weldable structural steel. Traditional hot rolling and normalizing can yield weldable steels with moderate strength up to S460N and toughness. A yield strength of up to 1100 MPa can be achieved for structural steels using the quenching and tempering procedure. Thermomechanical rolling, on the other hand, provides for grain refinement, allowing the carbon and alloy content of TM-steel to be reduced effectively when compared to normalized steel of the same grade [66].

The environmental impact of a particular weight of steel grows with increasing steel strength and alloying content. However, because improved strength results in lower weight, the overall environmental impact will be lowered significantly [67].

A study by Sperle, J, O et al [67] saw the environmental advantages of high strength steel compared to regular steel. Abrasion-resistant steel and structural carbon steel as heavy plate are featured in the study.
These steels have a low alloying element content and are quenched and tempered. The yield strengths of high strength steels range from 350 to 1400 MPa.

The result in the study is provided as a function of yield strength in terms of global warming potentials. The results are shown in figure 45.

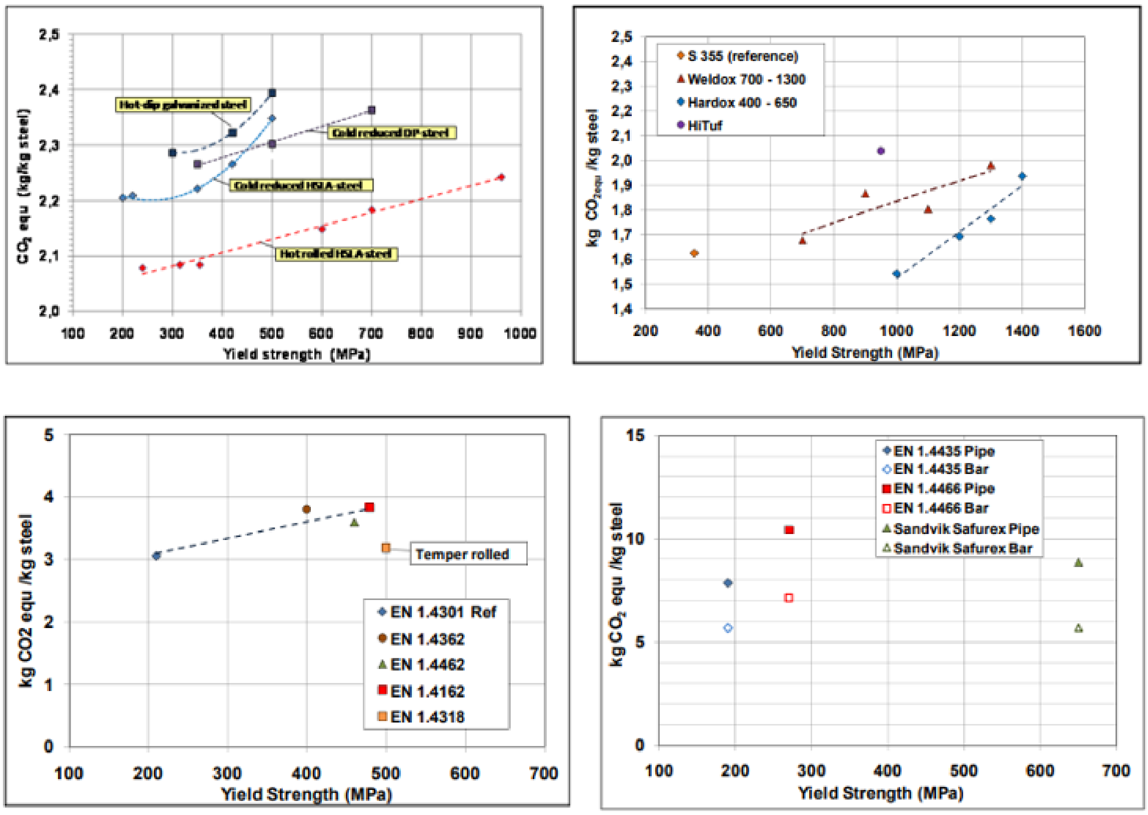


Figure 45: GWP as a function of yield strength. Top left) Steel produced at Luleå- Borlänge, Top right) Steel produced in Oxelösund, Bottom left) Stainless steel produced at Outokumpu, Bottom right) Steel produced in Sandvik [67]

Figure 46 shows the relative GWP for steel production based on the yield strength compared with the advantages with a lighter structure by using high strength steel in constructions.

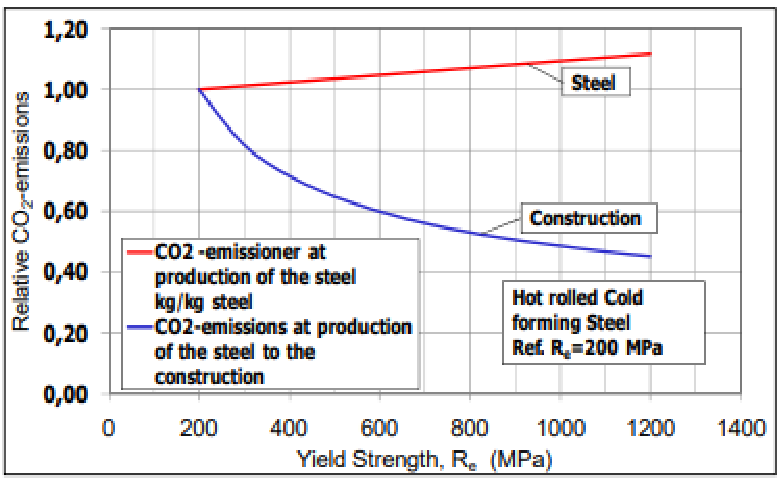


Figure 46: Relative GWP compared to yield strength [67]

When expressed per unit of steel weight, the Life Cycle Assessment of the selected carbon steel and stainless-steel manufacturing indicates, as expected, a minor rise in environmental effect with increasing steel strength. When comparing "cradle-to-gate" results per ton steel,

this means that high strength steel grades often have a greater environmental impact than standard steels. This is owing to higher alloy content and/or more complicated processing routes. However, because improved strength leads to less weight, the overall environmental impact will be lowered significantly.
Examples from this study illustrate that by replacing conventional steel with advanced high strength steel, it is possible to obtain a 25 percent weight reduction.

This method was used to develop the Friends Arena, Europe's second largest indoor stadium [68]. The roof trusses supporting the retractable roof are partially made of molybdenum-containing high-strength steel. Different grades of high strength steel were used in the various structural elements of the roof truss by the structural engineers to maximize the design. For a stadium of this scale, the result is a surprisingly light roof.

Steel can be strengthened in a variety of ways. Strength can be increased by simply adding additional carbon, but this might have a negative impact on steel's weldability and ductility. Instead, molybdenum is added to the steel to make it stronger without sacrificing its weldability. The molybdenum concentration in high strength steel can range from 0.1% to 0.5%, depending on the required strength level and plate thickness, as indicated in figure 47

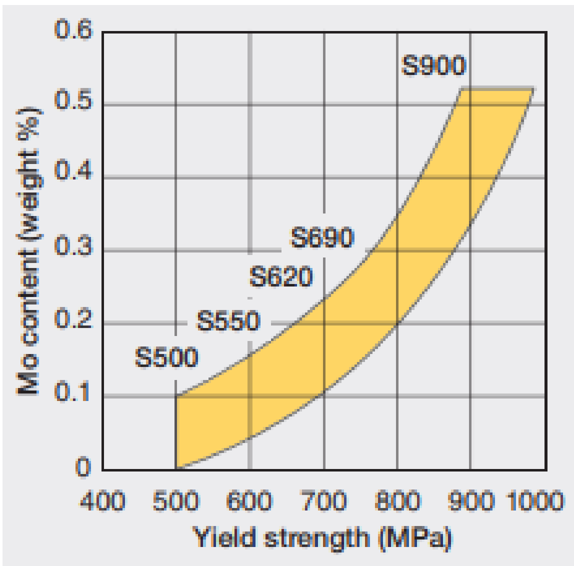


Figure 47:Molybdenum content based on required strength [68]

When compared to a roof made of normal S355 steel, the usage of high strength steel resulted in a reduction of 585 tons, or 13% of the total weight of the roof.

In terms of life cycle environmental impact, the lowest amount of steel used resulted in a great reduction in environmental impact. Taking into consideration the added benefit of transportation savings and steel recyclability at the end of life, the high strength steel retractable roof achieved an environmental saving of nearly 900,000 kg of CO_2 equivalent, or 17%, when compared to construction with all regular steel [68].

Lemma, M, S et al performed a case study of three bridge designs using high strength steel [66]. The bridge has five spans, with 80-meter internal spans and 60-meter end spans. The bridge is 360 meters long in total. The deck slab and non-structural bridge equipment have symmetrical transverse cross-sections about the bridge's axis. The bridge superstructure is 21.5 meters wide and supports four traffic lanes, two in each direction of which are 3.50 meters wide. The external shoulders are 2.0 meters wide and interior shoulders 0.75 meters wide. Both shoulders have barriers. The global and cross-sectional dimension of the bridge is shown in table 48.

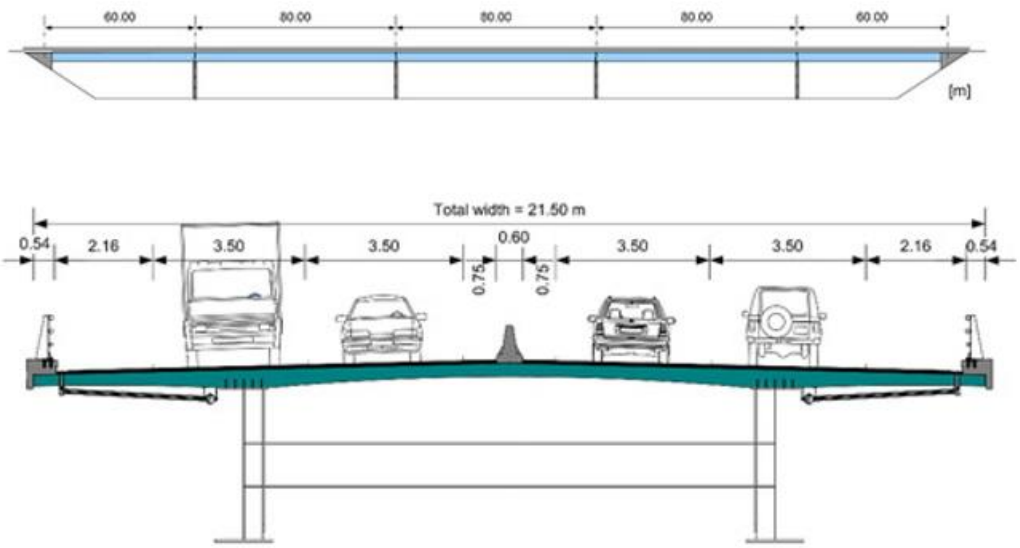


Figure 48: Global dimensions and cross-section [66]

Three different steel construction alternatives were explored to determine the benefits and drawbacks of employing higher-grade steel. In all three designs, the concrete slab's properties are kept the same. Design A uses standard steel grade S355 and follows current Eurocode design criteria. The steel grade S690 was used in Design B, and the design was based on current Eurocode's design criteria.

Bridge Design C uses the same S690 steel grade as Design B but investigates different post-welding treatments to improve fatigue behavior of the governing transverse stiffeners to bottom flanges welded joints, as well as possible Eurocode rule enhancements, such as improved design rules for verifying web plate buckling. This enables significant plate thickness reductions at the bottom flange and web in the span region. In addition, one longitudinal trapezoidal stiffener was installed on the exterior of the plate girder section, reducing the number of transverse stiffeners while enhancing web resistance. The dimensions of the beams are shown in figure 49, 50 and 51.

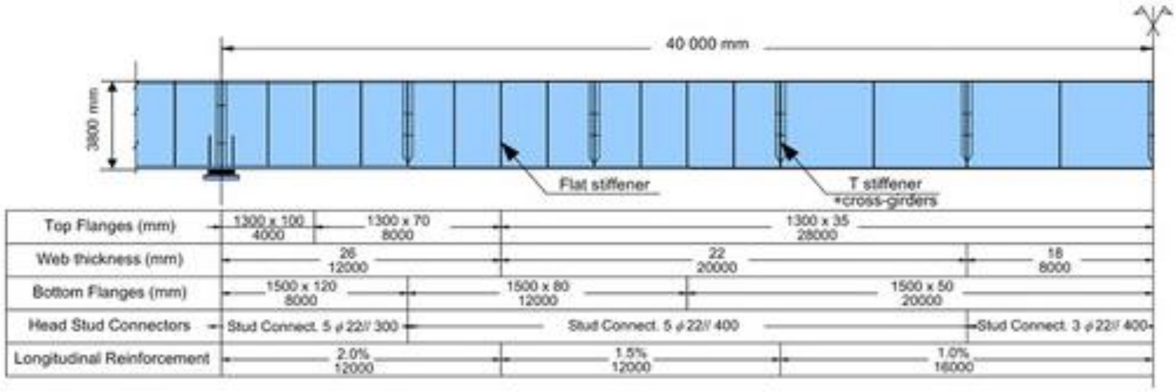


Figure 49: Design A [66]

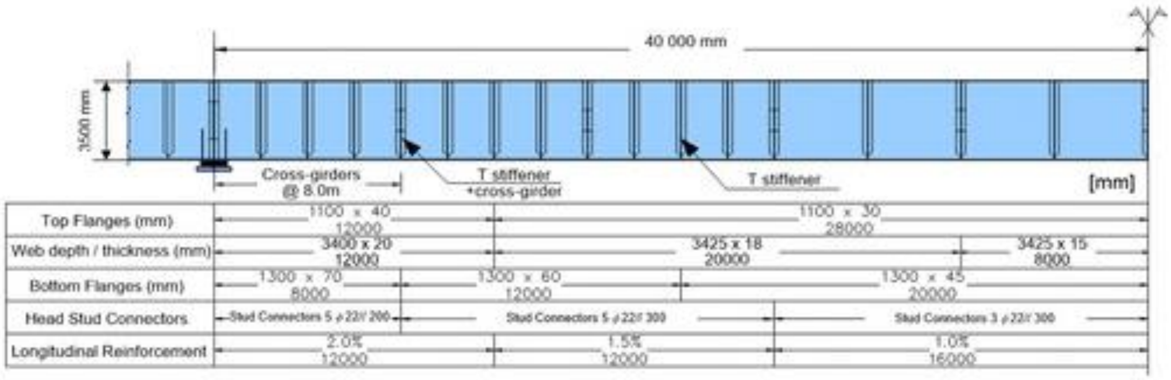


Figure 50: Design B [66]

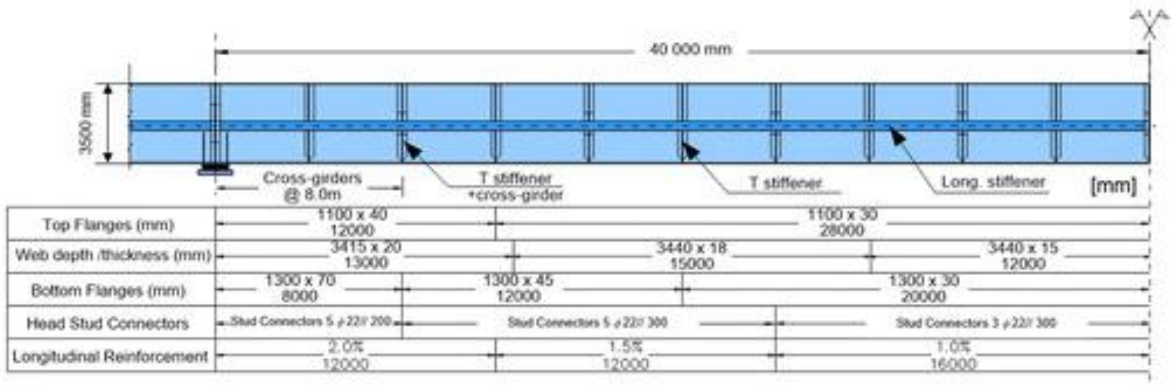


Figure 51: Design C [66]

Design details for the structural parts and material consumption of each design are given in respectively table 25 and 26.

Table 25: Table of design details [66]

	Design A	Design B	Design C
Steel grade	S355	HSS S690	HSS S690
Girder depth	3800 mm	3500 mm	3500 mm
Lower flange	Width: 1500 mm Thickness: 50-120 mm	Width: 1300 mm Thickness: 45-70 mm	Width: 1300 mm Thickness: 30-70 mm
Web	Thickness: 18-26 mm	Thickness: 15-20 mm	Thickness: 15-20 mm
Upper flange	Width: 1300 mm Thickness: 35-100 mm	Width: 1100 mm Thickness: 30-40 mm	Width: 1100 mm Thickness: 30-40 mm
Stiffeners	Transverse tee stiffeners every 2-4 meter	Transverse tee stiffeners every 2-4 meter	Longitudinal trapezoidal stiffeners and transverse tee stiffeners every 4 meter
Cross- girders	Plate girders 1-2 m depth Spacing: 8m	Plate girders 1-2 m depth Spacing: 8m	Plate girders 1-2 m depth Spacing: 8m
Welding wire rod	1237 kg	934 kg	810 kg

Table 26: Material consumption [66]

	Unit	Design A	Design B	Design C
Steel S355 J2	Ton	273,35	-	-
Steel S355 NL	Ton	102,30	-	-
Steel S690 QL	Ton	-	194,47	175,75
Steel S690 QL1	Ton	-	88,99	80,42
Shear studs	n^o	1974	2508	2508
Corrosion protection	m^2	2818	2757	2727
Welding wire rod	kg	1237	934	810

The results from the life cycle analysis for bridge design A are shown in table 27

Table 27: Life cycle assessment results for design A [66]

Impact category	Total	Material production stage	Construction stage	Operation stage	End-of-life % recycling stages
ADP fossil (MJ)	7.15E + 06	1.09E + 07	5.52E + 05	1.52E + 06	−5.79E + 06
AP (kg SO_2 eq.)	1.80E + 03	2.85E + 03	1.44E + 02	1.15E + 02	−1.31E + 03
EP (kg PO_4 eq.)	1.89E + 02	2.01E + 02	1.05E + 01	1.33E + 01	−3.55E + 01
GWP (kg CO_2 eq.)	5.20E + 05	9.96E + 05	5.05E + 04	2.66E + 04	−5.54E + 05
ODP (kg R11 eq.)	1.76E−02	2.57E−05	6.54E−07	6.79E−08	1.76E−02
POCP (kg C_2H_4)	3.41E + 02	5.78E + 02	2.77E + 01	2.91E + 01	−2.94E + 02

Bridge design A is set at the reference line when comparing the results from Design B and C.

The material production stage had the greatest environmental impact in all three designs. In the study research, both the construction and operation phases play a little role. Because the focus was on the structural steel portions of the girders, the operating stage had a small contribution. The LCA results for all three designs are shown in figure 52.

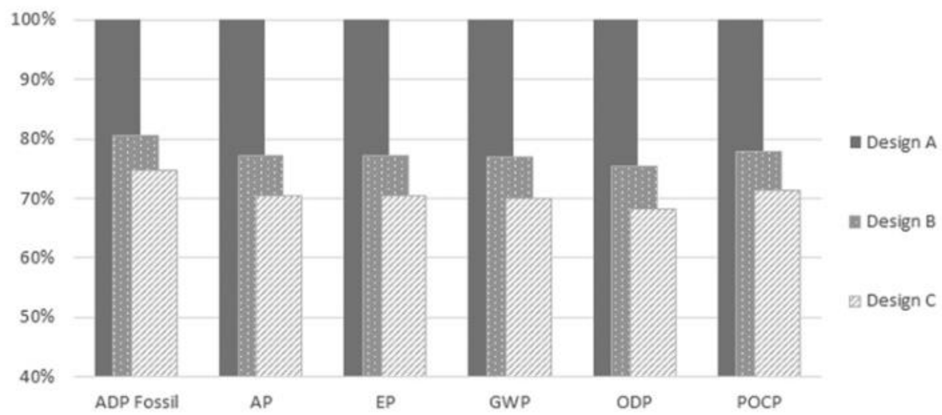


Figure 52: LCA results [66]

Credits (negative values) were acquired in all categories due to recycling at the end-of-life stage, with the exception of the ODP category, which had positive values. Bridge Design B, in comparison to Design A, allows for reductions of 20% to 25% in ADP and ODP, respectively. In comparison to Design A, Design C allows for even more reductions. In this scenario, the reduction varies between 25% and 32% for ADP and ODP, respectively. When comparing Designs B and C for the impact category of ODP, the latter indicates a reduction of up to 10%. In most impact categories, design B and C are preferable to design A in the material production stage.

In terms of the end-of-life stage, the fact that steel recycling has a positive impact (negative burden) allows design A to be more favorable than designs B and C. However, the consequences in the other stages outweigh this gain, which makes design A the least favorable when compared for the whole LCA assessment.

It is well known that using HSS in a structure provides a substantial benefit because it allows the structure to employ less materials to perform its purpose.
Because no environmental data for HSS is currently available, the data for common steel grades S355 and S690 were used. Taking this limitation into consideration, the reduction of steel in bridge Designs B and C resulted in better environmental performance than bridge Design A: Design B enabled a reduction of up to 25%, while Design C enabled a reduction of up to 32%.

6.3 Wood and timber bridges

Due to emissions associated to the fabrication of materials, mostly steel and concrete, bridge decks have the greatest environmental impact on short and medium span road bridges. Decks made of less emissions-intensive materials, such as wood, can help cut emissions. Ambitious projects like the timber Mjøsa Bridge are boosting awareness of the capabilities of timber bridge designs and challenging traditional bridge construction processes. However, there are several barriers to wider industry acceptance, particularly when employing lumber in bridge decking and bridge rehabilitation [69].

6.3.1 Oppstadåa and Vippa bridge

O'Born, Teyn et al conducted a study to see how timber would perform as material in bridges compared to concrete [69]. The study performed a case study of two bridges in Norway.
The bridge in the first case study was modeled by a previous network arch bridge design for the Oppstadåa Bridge in Norway. A typical network arch bridge is a light-weight steel bridge arch with an interwoven network of steel cables that crosses each other at least twice.
The Oppstadåa Bridge must accommodate 16 500 AADT and vehicle speed of 90 kilometers per hour. The main arch is a timber truss that was constructed according to the Eurocode series and is expected to last 60 years. The deck has a span length of 120 meters and has a driving width of 17 meters and a total width of 21 meters. The arch heigh and length is respectively 18 meter and 127 meters [70].

Figure 53: Left) Oppstadåa network arch bridge with timber arches, Right) Vippa bridge with concrete arches [69]

The existing Vippa Bridge in Norway is the subject of the second case study. Vippa Bridge is a concrete arch bridge with a concrete deck supported by transversal steel beams and steel hangers connecting to the arch. The Vippa Bridge was constructed in 1943 in accordance with 1930 bridge standards. The deck has a driving width of 6 meters, a total width of 7.5 meters, and a 50-meter free span. The bridge has a combined total load of 50 tons, with a maximum axel load of 10 tons.
The bridge deck for Vippa bridge will need to be rehabilitated, and one of the objects of the study was to design a timber deck alternative. Renovating an existing bridge with a timber deck is unusual, but it has happened before in Norway. The Hundorp Bridge, which was completed in 1924, was the first bridge to have its timber deck restored in 2010. The 200-meter deck was constructed of cross laminated wood, which increased load capability. Although it has the same load capacity, the Vippa Bridge is shorter than the Hundorp Bridge, with a total free span of 50 meters.

The original bridge deck for Oppstadåa bridge was a 60 cm deep concrete deck and a total volume of 1529 m3 concrete, with an extra 315 tons of reinforcing steel. With 3276 m3 glue laminated timber and 64.7 tons of pretensioning steel bars, the alternative timber bridge deck design has a thickness of 130 cm. Each bridge design's arch, arch support, and steel hangers are identical and unmodified from the prior analysis. Table 28 shows the material quantities for Oppstadåa timber arch and deck bridge design.

Table 28: Material quantities for both design for Oppstadåa bridge [69]

Element	Concrete deck	Timber deck	Unit
Timber, arch	1425	1425	m^3
Steel, arch support	86.2	86.2	tons
Steel, hangers	44.4	44.4	tons
Timber, deck (GL32)	-	3276	m^3
Concrete, deck (C30)	1529	-	m^3
Reinforcing steel, deck	314.8	75.0	tons

The Vippa Bridge's concrete deck has a total depth of 24 cm, requiring 72 m3 C30/37 concrete and 5.7 tons of reinforcing steel. The timber design will be 35 cm thick, with 105 m3 glue laminated GL32 timber and 4 tons of support steel required. Table 29 shows the material requirements for the Vippa bridge design calculations.

Table 29:Material quantities for Vippa bridge [69]

Element	Concrete deck	Timber deck	Unit
Timber, deck (GL32)	-	105	m^3
Concrete, deck (C30)	72	-	m^3
Reinforcing steel, deck	5.7	4.0	tons

The life cycle analysis for the Oppstadåa bridge shows the timber deck had better environmental performance in all of the seven categories compared to a concrete deck. Climate change emissions are the most useful metric. The timber deck of the Oppstadåa Bridge produced 31% fewer overall emissions than the concrete deck option. The replacement of emissions-intensive steel and concrete has resulted in a significant reduction in emissions. The concrete deck bridge produced 2032 tons CO_2-equivalents, while the timber deck bridge produced 1410 tons CO_2-equivalents. Freshwater and marine eutrophication, photochemical oxidant formation, and particulate matter formation are all reduced significantly by the timber deck bridge.

The results for Oppstadåa bridge are in figure 54 and 55.

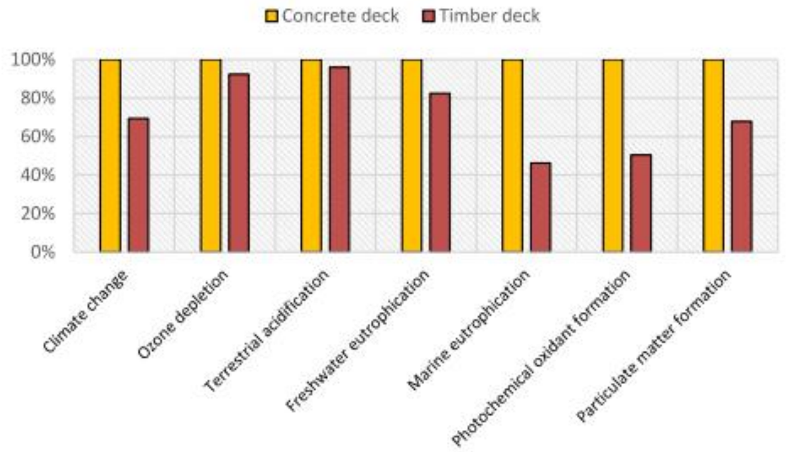


Figure 54: LCA results for Oppstadåa bridge [69]

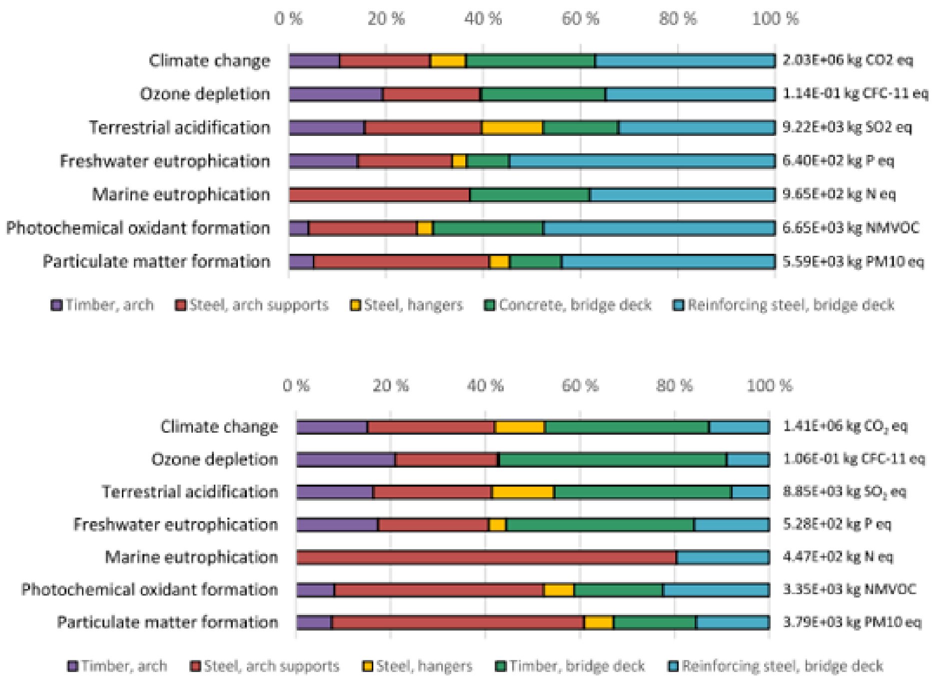


Figure 55: LCA results by components for Oppstadåa bridge. Top) Concrete deck. Bottom) Timber deck [69]

For Vippa bridge the life cycle analysis showed the environmental improvements were not as clear as for Oppstadåa bridge. In the categories of climate change, marine eutrophication, photochemical oxidant generation, and particulate matter formation, the timber deck had 65 percent fewer consequences than the concrete deck. In the categories of terrestrial acidification and freshwater eutrophication, the concrete deck did better. It should be noted that, with the exception of climate change impacts, overall emissions in each impact category were fairly modest. The most significant environmental benefit of building a timber bridge deck for the Vippa Bridge is the reduction in carbon dioxide emissions of more than 13 tons as compared to a concrete deck. Figure 56 shoes the results for Vippa bridge.

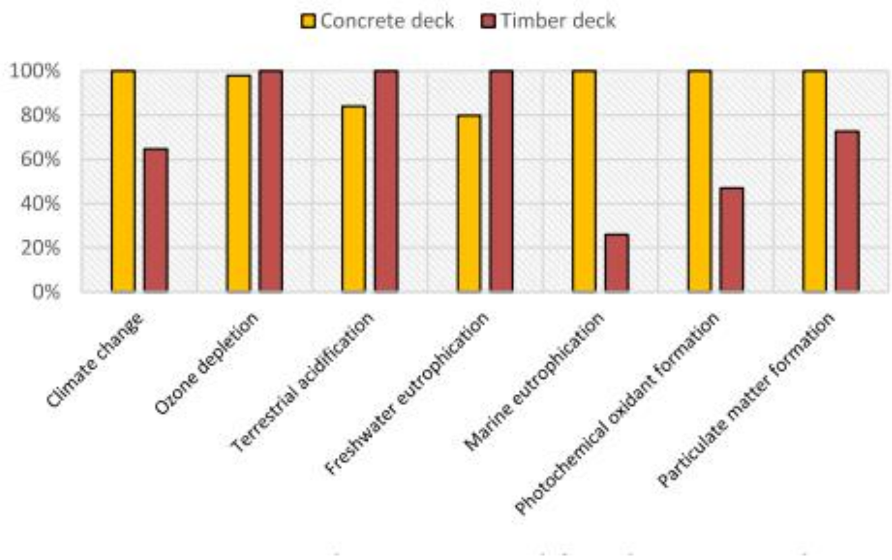


Figure 56: LCA results for Vippa bridge [69]

The CO_2-equivalent emissions reductions for the Oppstada and Vippa timber deck designs were determined to be 31% and 35%, respectively. When combined with reductions from another research by the same authors, the Oppstadåa Bridge design with a timber arch and deck results in a CO_2-equivalent emissions reduction of more than 61 percent when compared to a similar generic steel bridge design. This shows that, in order to reduce climate change consequences in road infrastructure, road planners should pay significantly more attention to using timber components in bridge design.

When using a timber deck solution, the displacements dictate the design, which can result in decks with enormous dimensions (even if the weight is light), especially for long spans. This is the situation with the Oppstadåa Bridge, which may or may not be a reasonable solution. However, for short spans, such as the Vippa Bridge, a timber deck provides a cost-effective and dimensionally acceptable alternative.

6.3.2 Mjøsa Bridge

Another study by Reyn O'Born [71] saw at the life cycle assessments for what will might be the world longest timber bridge with a length of 1650 meters. If the timber design is chosen, it will be more than 1000 meter longer than the worlds current longest timber bridge, Tynset bridge in Norway.

The bridge which was the case study is Mjøsa bridge located in Norway and crosses Norway's biggest lake. The existing 1420-meter Mjøsa Bridge, which has a daily average traffic of 13,000 cars, was built in 1985. The existing Mjøsa Bridge was designed to last 50 years [71].

A glue laminated (glulam) timber superstructure is one of the suggested ideas for the new Mjøsa Bridge. Because of concerns about the long-term durability and maintenance of timber structures, the research costs for building the timber bridge are significant. Intelligent design has mostly alleviated these worries, yet there is still some skepticism. Both the maintenance and the predicted lifetime of timber products are fraught with uncertainty. The biggest issue with most timber constructions is the possibility of moisture and wood-eating insects penetrating the surface, producing fractures and structural weakness.
If the timber bridge design proves too costly or difficult to construct, the Norwegian Public Roads Administration has also created a concrete alternative for the Mjøsa Bridge [71].

Figure 57: Design suggestions for the new Mjøsa bridge. Left) Concrete deck. Right) Timber trusses [71]

The new Mjøsa Bridge will be a four-lane interstate bridge capable of carrying up to 24,000 AADT and with a speed limit of 110 km/h. The construction length is 1650 meters, with 69-meter spans, except for the four middle spans between the steel towers. Here the span will be 120 meters. The bridge's total width will be 32.5 meters, with four driving lanes with a total driving width of 9.5 meters on each side, a 3-meter-wide bicycle lane on the southern side, a 3-meter-wide service lane on the north side, and the rest width used as shoulders [71].
Figure 58 shows the global timber bridge dimensions.

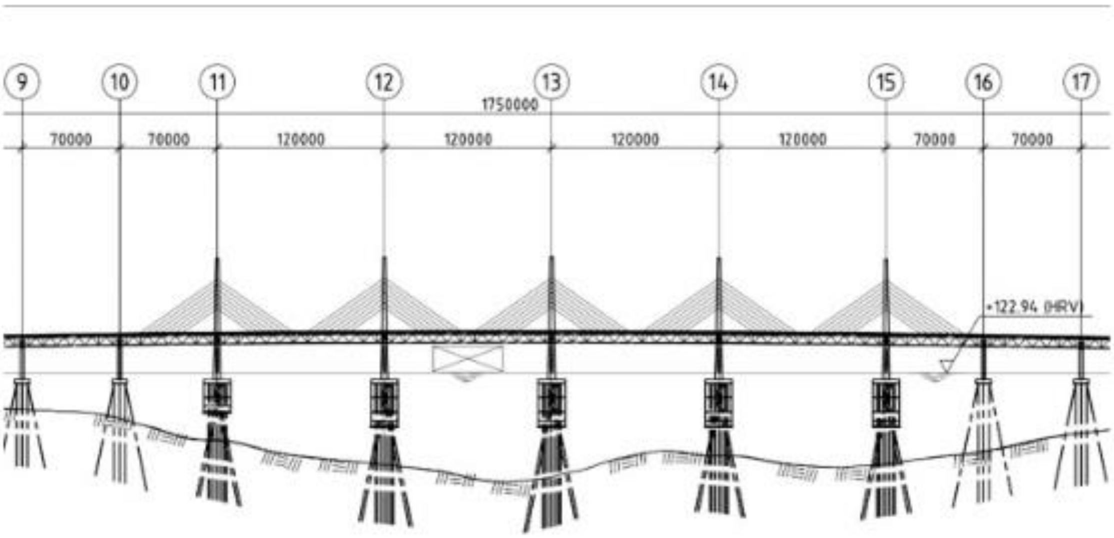


Figure 58:Dimensions for timber bridge design for Mjøsa bridge [71]

Each bridge features five identical steel towers that rise 53 meters above the bridge deck. The concrete bridge has a distance of 138 meters between each tower, whereas the timber bridge has a distance of 120 meters. The tower's components underneath the bridge deck are made of concrete, while those above the deck are made of steel. The towers will be joined to the bridge superstructure via steel cables and are manufactured from pre-formed steel components and welded on site [71].

Glue laminated timber trusses will be used to construct the timber bridge superstructure. The timber bridge sections will be assembled in 70-meter prefabricated spans and transported to the job site by trucks. The timber superstructure will have a total height of roughly 9 m, with each beam having a width of 1.6 m and a height of 7.3 m. Steel bolts and steel plates will connect the beams, which will be coated with creosote. As illustrated in figure 59, the superstructure's overhanging concrete deck provides adequate protection from direct water exposure. The angle between the overhang and the deck edge must be at least 30 degrees [71].

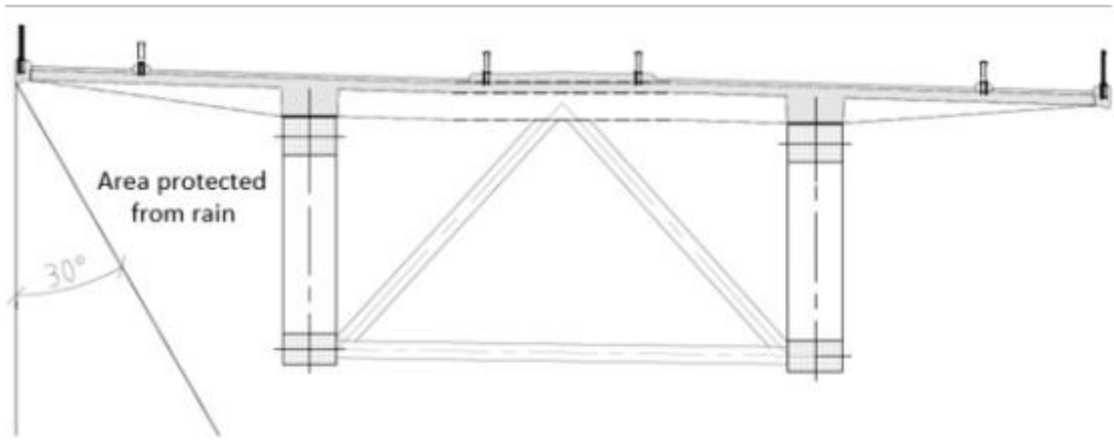


Figure 59:Cross-section of the timber bridge design for Mjøsa bridge [71]

The superstructure of a concrete bridge is normally made out of steel reinforced concrete box girders with spans of 70 meters. Additional steel supports are added to the transverse and length directions of the box-girder spans. The total height of the concrete bridge superstructure is approximately 4.1 meters. The concrete bridge features a deck that is approximately identical to the deck of the timber bridge.

The timber bridge deck requires no major maintenance, but it does require frequent visual checks to ensure that it remains dry. If cracks are discovered in the superstructure, an epoxy can be used to patch them, and another coat of sealer or paint can be applied to prevent further moisture penetration. Because of the increased overhang from the bridge deck, this form of moisture cracking is plausible but uncommon.

The study looked at three different designs for Mjøsa bridge:

- Concrete bridge
- Timber bridge (T)
- Timber bridge that provides for end-of-life treatment of the timber materials (T) (T-AI)

The T-AI timber bridge expands the life cycle assessment by assuming that the timber materials are burned for energy and heat in an incinerator, therefore the timber from the bridge can reduce the necessity of power from the Norwegian electricity mix and district heat systems.

The material quantities for each bridge design are shown in table 30.

Table 30: Material content for Mjøsa bridge [71]

	Concrete (c)	Timber (T-AI)	Timber (T)	Unit
Asphalt, included repaving	25,011	24,955	24,955	$tons$
Concrete	72,253	57,556	57,556	m^3
Creosote	-	100	100	$tons$
Earthworks	16,425	22,610	22,610	m^3 earth displaced
Explosives	1035	1035	1035	m^3 $rock\ blasted$
Glue laminated timber	-	18,500	18,500	m^3
Guadrails	10,524	10,500	10,500	m
Reinforcing steel	18,650	10,507	10,507	$tons$
Steel	2619	3233	3233	$tons$
Steel piles	29,524	27,461	27,461	m
Energy recovered (heat)	-	85,896	-	GJ
Energy recovered (electricity)	-	11,581	-	GJ

The timber design required a total of 18,500 m3 of wood. Concrete consumption was 25% greater on the concrete bridge than on the timber bridge. The timber bridge required 38 percent additional earthworks, primarily for the abutment. The concrete bridge required 77 percent more reinforcement in the concrete elements than the timber version, resulting in 77 percent more reinforcing steel being used. Due to a modest design modification in the tower and the additional steel necessary to protect and construct the timber sections, the timber bridge used 23 percent more steel than the concrete bridge. Due to a modest design adjustment in the positioning of the deep-water foundations and the higher total weight of the bridge, the concrete bridge featured 7% more steel piles than the timber version [71].

From the results of the LCA analysis in the study, the timber bridge designs performed better than the concrete bridge in all aspects of the assessment. The results are shown in figure 60.

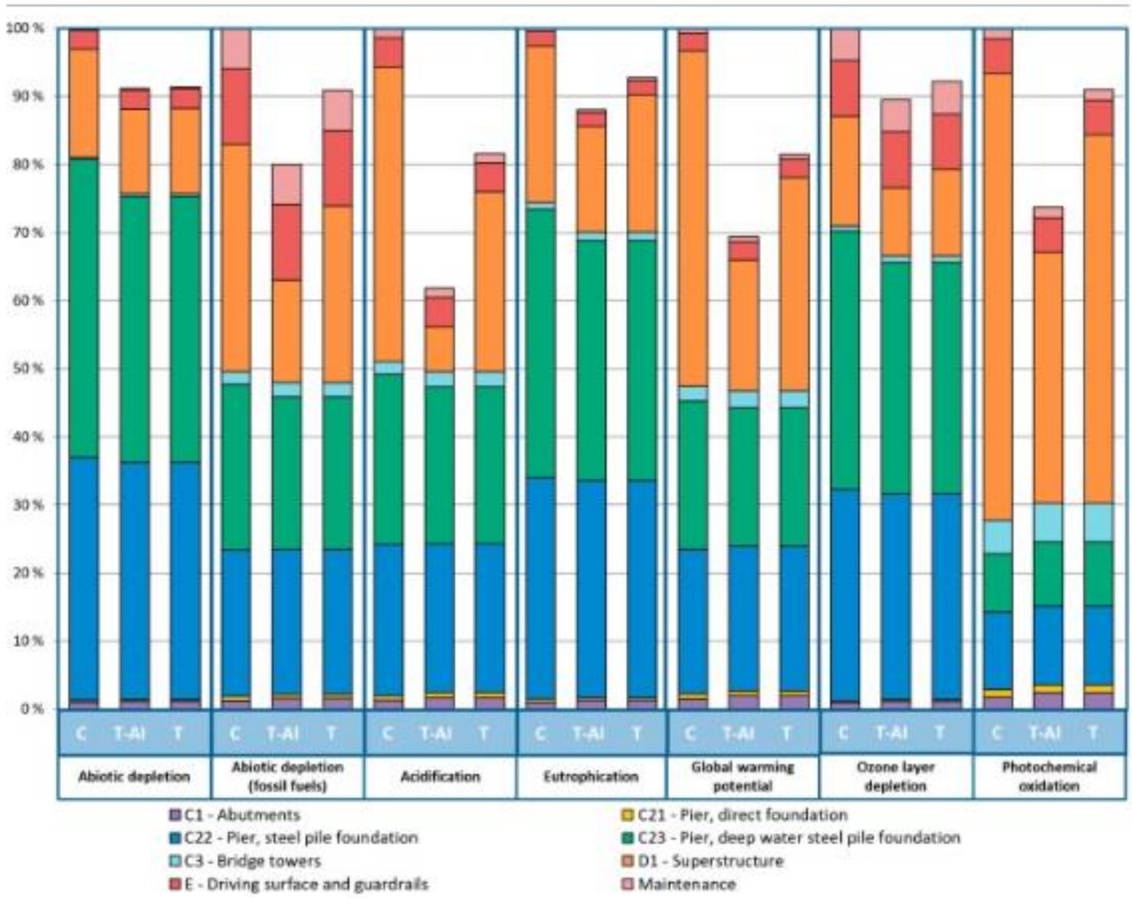


Figure 60: LCA results of Mjøsa bridge [71]

The superstructure is where the highest variation in climate change emissions occurs, accounting for 49 percent, 31 percent, and 19 percent of total CO_2-equivalent emissions for concrete, timber, and timber-AI bridges, respectively. The timber components are employed in the superstructure of the timber bridge design, resulting in the greatest reduction in emissions due to lower concrete and steel demand. The emission from each material is shown in figure 61.

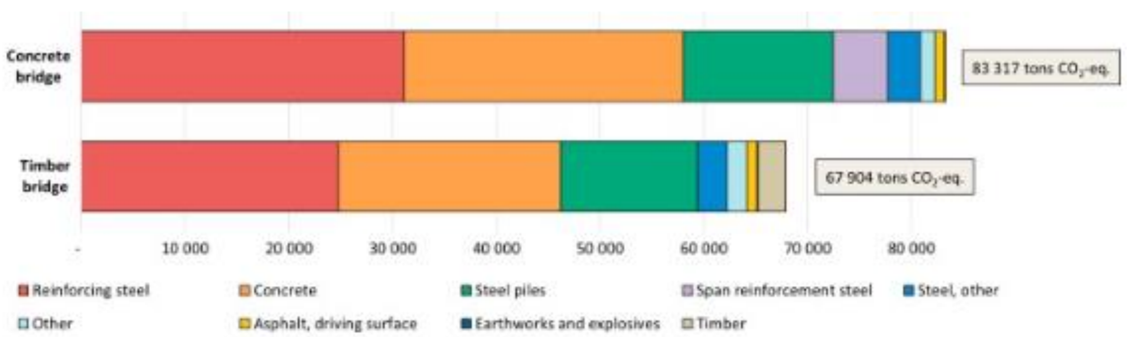


Figure 61: Emission based on material for Mjøsa bridge [71]

7. Material and design change on Kjøkøysund bridge - case study

7.1 Kjøkøysund Bridge

Kjøkøysund bridge is in Fredrikstad and connects Kråkerøy and Kjøkøy. It is a concrete box bridge with a total length of 375m. The bridge has 6 spans and the main span over Kjøkøysundet is a cantilever bridge. The length of the main span is 110 m and has a sailing height of 25 m. The rest of the spans has been cast in place on scaffolding. It was projected by the consulting firm Taugbøl og Øverland AS and has stood since 1970. This bridge is a part of country road 108, and it functions as the only exit artery from Fredrikstad out to the Hvalerøyene [72].

A condition assessment has been done on the existing bridge, and the possibilities of upgrades and reinforcements have been investigated. The conclusion of this work is to tear the existing bridge and construct a new one next to it. Because of traffic congestion the existing bridge must stand, until the new bridge is constructed.

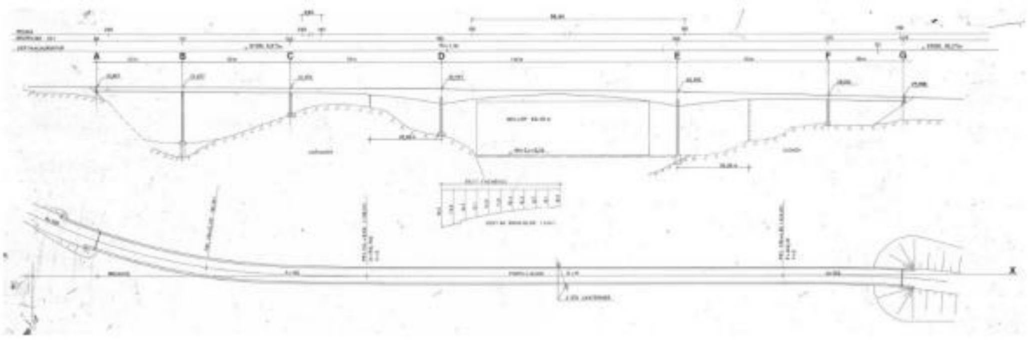


Figure 62: Existing Kjøkøysund Bridge [72]

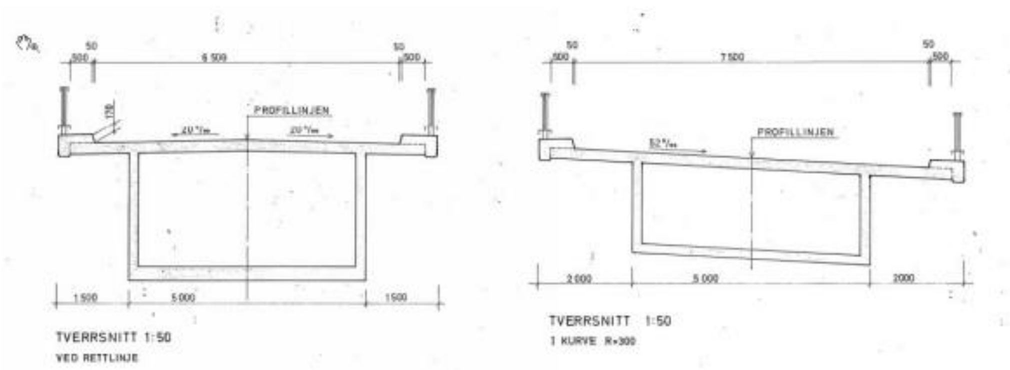


Figure 63: Cross section of existing Kjøkøysund Bridge [72]

The new bridge is recommended to be a cantilever bridge in prestressed concrete. The bridge will have 6 spans (43 + 59 + 76 + 146 + 80) m with a total length of 404 m, which makes the new bridge a bit longer. The superstructure will use post-tensioned cables. Cable ducts are set up after tensioning to provide absolute cooperation with the concrete. To make it simpler and more efficient when correcting unexpected long-term effects like scratching and deflection, an extra vouter should be inserted in the cross section [72].

In the main span the height of the construction will vary from 7,4 m in axis 4 and 5 to 2,9 m in the middle of the span. From axis 1 to axis 3 there will be a constant construction height of 2,9 m.

The bridge will have a carriageway with two lanes with the smallest guide width of 9,0 m and walking and cycling lane with a constant width of 3,0 m. There will be a separation between the driving lanes and the walking and cycling lanes with a low inner railing in steel. The lowest width between the railing will be 12,55 m in the main span between axis 4 and 5. From axis 1 to axis 3 the width will expand to a maximum of 15,3 m, this means the railing needs to be moved to meet the requirements of sight. Another reason for the width expansion is the curvator the bridge gets. In the last part of the bridge from axis 5 to axis 6 the width does not expand because of sight requirements, since the railing will not hinder the sight, but the width requirements because of the curvator will give an expansion of 0,4 m for each driving lane, which gives a total of 0,8 m width expansion in this part of the bridge [72].

The bridge cross-section is designed with constant width on the box part. The variable width on the bridge deck needs to be solved by varying the length of the cantilever wings.

There will be different columns used for different axis in the bridge. In axis 2 and 3 there will be two round columns with a diameter of 1200mm in both axes. The reason for this is to give it a simpler and more open, aesthetic expression than the alternative with disc columns like the bridge has today. In axis 4 and 5 they have chosen two parallel disc columns in each axis to make the columns less towering and let more light in. This is especially important for axis 5 which comes close to existing buildings, as seen in figure 65. Both the solutions are considered to give cost savings, even though in axis 4 and 5 the columns must be braced temporarily in the construction phase.

All the columns will be monolithically clamped in the superstructure, which gives the bridge bearings only at the land vessels. The bridge is founded on rock in axis 1, 2, 3, 4 and 5. The land vessel in axis 6 will get steel foundations in the inflow filling.

Both land vessels get a bridge joint and a versatile and side-mounted bearing. Joint construction should be subdued to avoid unnecessary noise, a solution for this could be multi-element joints with sliding plates. The land vessels are designed with joint rooms according to N400 for access and inspection of both stock and joint. The access to the joint rooms will be through a door in the land vessels on the walking- and cycling side. From the joint rooms there is an entry to the bridge box through manholes in the end cross member, for inspection and maintenance of installations [72].

New bridge:

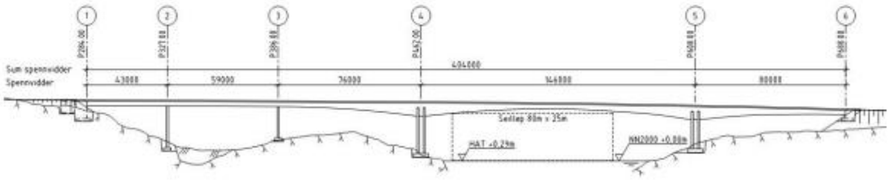


Figure 64: Suggestion for new Kjøkøysund bridge from SWECO from the side [72]

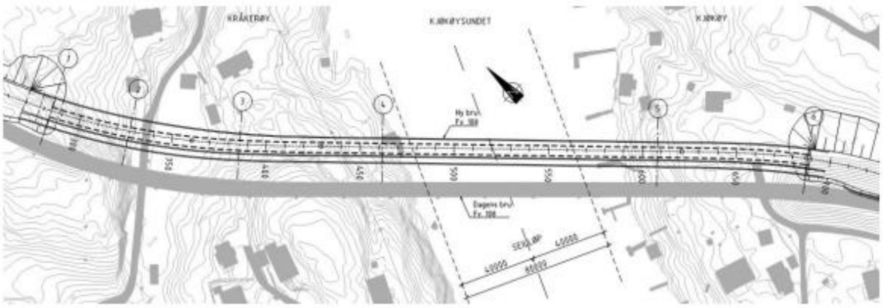


Figure 65: Suggestion for new Kjøkøysund bridge from SWECO seen from above [72]

7.2 The use of low carbon concrete on Kjøkøysund bridge

When constructing a bridge, it is important to not only look at it as a road for crossing an obstacle. There are several things to be considered when constructing a bridge, such as nature and how to accomplish a balance between the landscape and the bridge. To get a good result, the choice of construction type and choosing of materials, design and properties is crucial.

Beam box bridges in concrete are one of the most used and applicable bridge types in the world. This is because it has properties that embrace load capacity, torsional rigidity, one does not need to consider whether the bending moment is positive or negative and also properties to be produced as both cast-in-place and prefabricated concrete.

In Kjøkøysund bridge we have these beam boxes. On the box component, the cross section is created with a constant width. The problem of varying bridge deck width is solved by varying the length of the cantilever wings.

The highway has a variable crossfall of +/- 8%, whilst the pedestrian and cycling path has a constant crossfall of 2% in the direction of the outer railing. By rotating the entire bridge superstructure / cross section around the bridge, the crossfall can be picked up. The longitudinal axis changes in accordance with the change in the carriageway's transverse slope. This makes the bridge's construction easier on both sides in terms of formwork and reinforcement [72].

The concrete that will be used in the making of the new bridge is set to be B35/45. This is a good choice, as it will meet the requirements necessary for the bridge to be sustainable. But in this thesis, we will look into the possibilities to use a more environmentally friendly concrete in the cross-section. As mentioned, low carbon concrete is the future of the concrete we know today.

Since the Kjøkøysund bridge is a cantilever bridge, and low-carbon concrete has a longer curing time, challenges arise during casting. When the first bridge was made, there was 10 casting stages. The casting stages was planned to have this course:

- Day 1: The previous section is clamped, and the formwork carriages are relocated in preparation for the casting of the new section.
- Day 1-3: Slack reinforcement binding and tension pipe placement for prestressing reinforcement.
- Day 4: New section casting.
- Day4–7: Concrete hardening to the requisite strength for tensioning.

If everything went as it should the cantilever span was constructed in 11 phases, with a total construction time of 70 days. The stilas are scheduled to firm for three days, culminating in a total construction time of 73 days [72].

The challenge now is the curing time of low carbon concrete. The idea is to have a combination of two low carbon concrete types, in two distinct parts of the cross-section. There is a possibility to cast the lower part of the cross-section with low carbon class A, and the upper part (the bridge plate) with all its cables could be cast with low carbon class B. Since high strength before clamping is really only needed locally around the clamping anchor heads. The cables could anyways not be tightened until after 2 days (48 hours according to proccesscode 2: R762).

Since the cross section then will consist of two parts with somewhat different material properties, this can be solved by considering it as one cooperative cross-section in the design. This will i.e. provide requirements for additional vertical joint reinforcement through the cast joint between the two parts, but in principle this is only a question of design / detailing. And strictly speaking, the principle of combining at. A and B in this way limited to FFB bridges but can be used more generally.

To find out how this change of concrete will affect the bridge, different types of low carbon concrete from different distributors needs to be analyzed. An EPD of the different types of low carbon concrete will be used, and there will be a calculation to check which is the most environmentally friendly, and if it is more beneficial than the already suggested concrete.

7.2.2 Environmental impact from low carbon concrete

Different types of concrete by different distributions have been chosen and analyzed to find out which gives the lowest CO_2 emissions in the stages A1-A4. Each distributor has its own EPD for its different concrete products.

The concrete chosen to be most suitable for Kjøkøysund bridge is B35 M45. There has been a calculation of GWP for three variations that could be used on the main span of the bridge, which is the part where cantilever-method is used. One where the cross-section consists of only concrete B35 M45, another with a combination of low carbon B and low carbon A, and the last one consisting of only low carbon A.

These three variations have been calculated for three different distributors, which gives a total of nine scenarios.

Concrete B35 M45 is a type of concrete that’s gets used on agricultural structures as well as structures near the coast. B35 means that it has a compressive strength of 35 MPa, while the M45 stands for the water content. This is believed to have a higher CO_2 emission than the other two options, but a calculation must be done to verify this. EPD’s from Betong Øst, NorBetong and Vestfold Betong is used for the calculation.

The calculation requires GWP from the chosen concrete, and the volume of the cross-section. The stages A1-A3 is combined and calculated together, while stage A4 which is the transportation stage to the construction site is calculated separately. The dimensions of the cross-section is given in figure 66 [72].

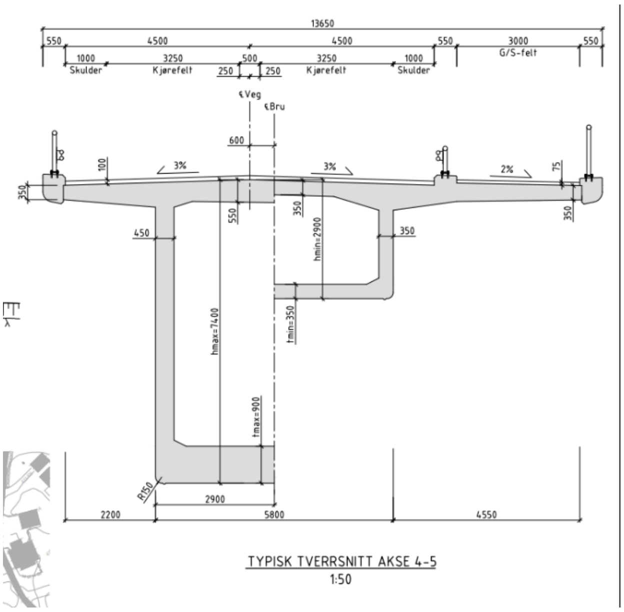


Figure 66: Cross section of the new suggested Kjøkøysund bridge [72]

The length of the cross-section that the volume has been calculated on is 1m. This gives a total volume of 13,19 m^3.

Table 31: Kjøkøysund bridge cross section dimensions. Calculations are based on the cross- section properties given in the report [72]

Volume of Kjøkøysund bridge box								
Top flange	0,48	m	Web width	0,42	m	Bottom flange width	2,9	m
Bridge width	13,65	m	Web height	5,42	m	Bottom bridge thickness	0,72	m
Bridge length	1	m	Bridge length	1	m	Bridge length	1	m
V=	6,60	m^3	V=	4,51	m^3	V=	2,08	m^3
Total Volume=	13,19	m^3						

The GWP for the concrete chosen is taken from the EPD's the distributors have provided. Figure 67 shows the GWP for stage A1-A4, from Vestfold Betong.

Miljøpåvirkning (Environmental impact)

Parameter	**Unit**	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,04E+02	9,08E+00	4,51E+00	3,06E+00

Figure 67: Environmental impact for concrete B35 M45 (Vestfold Betong) [Appendix K]

Miljøpåvirkning (Environmental impact)

Parameter	**Unit**	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00

Figure 68: Environmental impact for concrete B35 M45 (Betong Øst) [Appendix G]

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,31E+02	8,27E+00	4,76E+00	2,03E+00

Figure 69: Environmental impact for concrete B35 M45 (NorBetong)[Appendix I]

When it comes to stage A4, which is the transportation of the material to the construction site, the calculation is a bit different. The GWP is given in the same EPD, but transportation method and distance are a key part of the total CO_2 emission. A shorter distance from the distributor to the construction site could have a magnificent influence on the total CO_2 emissions. The calculation has been done on the same three distributors. To do the calculation, a transport calculator provided by Østfoldforskning AS is used.

The data needed to use the calculator is the weight of the concrete that is going to be transported, the CO_2-eq, the method for transportation and the distance from the factory to the construction site.

Our supervisor Thorbjørn Valnes from Sweco has done a simplified CO_2 assessment on a concrete bridge compared to a steel girder bridge. Where he calculated the total CO_2-emission for the volume of the bridge box cross-section per meter. This was then sent to the ones responsible for the environmental calculations in Sweco. The assessment was approved by them and explained that this could be used in general calculations regarding bridges. In this thesis, it has been chosen to make a more comprehensive assessment, with different EPDs and the use of accurate data related to the bridge. Where an attempt has been made to calculate the choice of material that leads to the least CO_2 emissions.

Mengder pr. m bru		CO2-ekv.				Tot. CO2	
3,7	m3/m	360	kgCO2/m3	1332	kg/m	2590	kg/m
740	kg/m	1,7	kgCO2/kg	1258	kg/m		
2,3	tonn/m	1,7	kgCO2/kg			3910	kg/m

Figure 70: Simplified CO2-assesment of a bridge, with concrete and steel [Appendix E]

		CO2-ekv.				Tot. CO2	
3,7	m3/m	290	kgCO2/m3	1073	kg/m	1961	kg/m
740	kg/m	1,2	kgCO2/kg	888	kg/m		
2,3	tonn/m	1,2	kgCO2/kg			2760	kg/m

Figure 71: Simplified CO2-assesment of a bridge, with concrete and steel [Appendix E]

		CO2-ekv.				Tot. CO2	
3,7	m3/m	290	kgCO2/m3	1073	kg/m	1591	kg/m
740	kg/m	0,7	kgCO2/kg	518	kg/m		
2,3	tonn/m	0,7	kgCO2/kg			1610	kg/m

Figure 72: Simplified CO2-assesment of a bridge, with concrete and steel [Appendix E]

The three figures above show the results for total CO_2-emissions per meter, for three different types of material. The first column is the amount per meter bridge of the cross-section volume. The second row shows CO_2-eqv of the different types of material, he has in this calculation only used typical numbers instead of checking the specific EPD for each material. The last column shows the total CO_2-emission in kilograms per meter.

7.3 Steel box girder alternative for Kjøkøysund bridge

For a steel box girder bridge the reference dimensions are taken from Randstadelva bridge in chapter *8.2.1.1*. With an assumed plate thickness average of 20 mm, the weight of the steel is 2,8 ton/m.

Steel from BGROUP is manufactured in Vilnius in Lithuania. The transport method for stage A4 is selected to be 32-ton lorry with Euro 5 engine. The distance is considered to be 1900 km, fuel consumption is set as 0,044 l/km with and the capacity utilization included return is 26,3 %.

The result from the calculator is shown below. For one meter of steel box girder with steel from BGROUP, the GWP from transport in stage A4 is 748 $kg\ CO_2 - eqv$.

Detaljert resultat transport

Navn	km	GWP (kg CO_2 -eq)	ODP (kg CFC11 -eq)	AP (kg SO_2 -eq)	EP (kg PO_4^{3-} -eq)	POCP (kg C_2H_4-eq)	ADPM (kg Sb -eq)	ADPE (MJ)
Lastebil over 32 tonn, EURO 5, 25 % Fyllingsgrad	1905,00	748,8981	0,000145000	2,473775000	0,566218000	0,124984000	0,002223000	11709,9775
Totalt	1905,00	748,8981	0,000145000	2,473775000	0,566218000	0,124984000	0,002223000	11709,9775

Figure 73: Results for transport emission for steel from BGROUP from the transport emission calculator in LCA.no

For high strength structural steel from MetaCon the raw materials are from Luxembourg, while the products are manufactured in Norway. This means the transport from production facility to the Norwegians suppliers' warehouse at Rakkestad in Norway is included in the production stage (A1-A3). The transport method from warehouse to building site is chosen to be >30-ton truck with EURO 5 engine. The fuel consumption is considered as 0,022 l/km and the distance from Rakkestad to Kjøkøysund is 47,6 km. For one meter of steel box girder with steel from MetaCon, the GWP from transport in stage A4 is 12,31 $kg\ CO_2 - eqv$

Detaljert resultat transport

Navn	km	GWP (kg CO_2 -eq)	ODP (kg CFC11 -eq)	AP (kg SO_2 -eq)	EP (kg PO_4^{3-} -eq)	POCP (kg C_2H_4-eq)	ADPM (kg Sb -eq)	ADPE (MJ)
Lastebil over 32 tonn, EURO 5, 50 % Fyllingsgrad	47,60	12,3138	0,000002000	0,040116000	0,008987000	0,001999000	0,000029000	193,1132
Totalt	47,60	12,3138	0,000002000	0,040116000	0,008987000	0,001999000	0,000029000	193,1132

Figure 74: Results for transport emission for steel from MetaCon from the transport emission calculator in LCA.no

For stage A4, steel from ALFA ACCIAI group south in Italy is transported with ship. The distance is approximately 5600 km. For one meter of steel box girder with steel from Elfa ACCIAI, the GWP from transport in stage A4 is 45,25 $kg\ CO_2 - eqv$

Detaljert resultat transport

Navn	km	GWP (kg CO_2 -eq)	ODP (kg CFC11 -eq)	AP (kg SO_2 -eq)	EP (kg PO_4^{3-} -eq)	POCP (kg C_2H_4-eq)	ADPM (kg Sb -eq)	ADPE (MJ)
Båt, internasjonal	5607,00	45,2508	0,000000000	0,184725000	0,064713000	0,008747000	0,000016000	663,7804
Totalt	5607,00	45,2508	0,000000000	0,184725000	0,064713000	0,008747000	0,000016000	663,7804

Figure 75: Results for transport emission for steel from ALFA ACCIAI group from the transport emission calculator in LCA.no

7.4 Different types of bridge design

A pre study was conducted by Sweco to see if there are any other bridge types that could be used [73]. For kjøkøysund bridge there are several alternatives bridge types based on the length of the main span and the topography. Alternative bridges can either be cable stay bridges, arch bridges or truss bridges [73].

In order for a vessel to pass under the bridge the sailing width and height must be respectively 80m and 25m.

Since the bridge is 400 meters with a main span of 114 meters, cable stay, and suspension bridges design would not be cost effective. Because of the curvature at both ends it may be difficult to mount the bridge decks outside the main span and the anchorage.

For bridge types where cable is the load bearer, a cable stayed bridge is more suited at these spans. Like the suspension bridge, the bridge tower needs to be in pairs which will lead to a bigger areal footprint and be annoying for the residents in the neighborhood.

Another option is arch bridges. These can either be overgoing or undergoing arches. Since there are short distances between each pilar or cable the bridge decks can be relatively thin. This will give a slender bridge which is aesthetics appealing. In order to get slender decks for the bridge which is not in the main span the pilar needs to be placed closer. This can interfere with the buildings nearby.

Figure 76: An arch bridge can be aesthetics appealing. This is Svinesund Bridge at the border of Norway and Sweden [74].

The pedestrian road can be built inside the bridge decks and will give protection against noise and dust from the traffic. This will also cause shorter width of the deck and reduce material use. For Kjøkøysund bridge, the width can be reduced with 3,5 meters since the pedestrian road and pedestrian railings can be neglected. Because of the sight obstruction from the railings it is required, according to Norwegian road authority's handbook N 101: *Rekkverk og vegens sideområder*, to expand the width with atleast 2,2 meters. This means the effective width reduction is 1,3 meters.

From the literature study these types of bridges are suitable for Kjøkøysund bridge:

- Cantilever bridge with low carbon concrete class C

- Cantilever bridge with low carbon concrete class A in girder and Class B at deck

- Cantilever bridge with low carbon concrete class A

- High strength concrete beam girder bridge

- Steel box girder bridge

- High strength steel box girder bridge

- Timber truss arch and deck bridge

In order to determine which one of these bridge designs has the lowest global warming impact; it have been performed a life cycle assessment for each one of the designs and compared them with each other.

7.5 Life Cycle Assessments for seven bridge designs suited for Kjøkøysund bridge

The software used for the life cycle assessment is OneClickLCA. One Click LCA has several tools for life cycle analysis of infrastructure constructions [75]. In this report it has been chosen PAS 2080 carbon tool since it covers all stages from cradle to grave in addition to the benefits stage. For transportation calculations it is calculated automatically by software based on the construction site. For this LCA the transportation region was set as *Norden*. End of life calculations method is also calculated by the software, by choosing the *Material-locked* option.

Based on the literature study, 7 bridge designs with different material or design are suitable for Kjøkøysund bridge. The designs are the same as mentioned in chapter 7.4.

7.5.1 System boundaries

The system boundaries for the LCA are considered to be production, transport, maintenance, and end of life stage.

When it comes to protection of the structures, the repainting for steel girder bridge and recoating of timber structures are included. The concrete structures do not require any surface protection beyond the concrete cover thickness, which is important, so corrosion doesn't attack the reinforcement steel.

Since the load and vehicle volume can be considered the same for all the bridges, the operation stage is excluded in the life cycle analysis. Except for stage B1 for concrete structures, here it is assumed the cement in the concrete will be carbonating during the whole service lifetime.

End of life stage includes the scenarios from C1 to C4 and stage D. In the software there are three scenarios for end-of-life stage scenarios. For this study it has been chosen the material-locked option which are recommended. This option will automatically calculate the emissions for the end-of-life stage based on EN 15978/ EN15804 [76]. If the steel is manufactured from scrap, then the software assumes the steel no longer has recycling potential [9]

The service life for the construction is set as 100 years for all the bridge design, except for the HPC. For HPC design it is assumed the service life can be extended to 200 years, based on the better durability performance [56].
The stages which are included in the LCA is shown table 32

Table 32: System boundaries which are covered in the life cycle assessment

Production Stage	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
Construction stage	Transport to building site	A4
	Installation	A5
Use and operational stage	Use and application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End- of- life stage	Demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4
Benefits stage	Reuse	D
	Recovery	D
	Recycling	D

7.5.2 Inventory data

The inventory data covers the material consumption for each bridge design. In this assessment the information of technical data for the environmental load is taken from the software database. The materials which have been chosen are based on the literature study or similar variants with lowest environmental impacts as the main criteria.

Only the material for the main spans is considered, since this is where most of the bridge superstructure materials are located. Even though the design might have different self-load and influence the foundations and pillars in different ways, in this assessment it is assumed the same for all designs. The material quantities for the foundation footing and pillars are taken from the pre- study report by Sweco for Kjøkøysund bridge [72].

7.5.3 Technical data and assumptions

The material quantities data for the design bridges are collected from the literature study or based on technical drawings of similar bridge design.
The reference bridge design is the concrete cantilever bridge as designed in the pre- study by Sweco [72].

The results from life cycle assessments in the literature study show that the major contributor of emissions comes from the material concrete, steel, timber, reinforcement and asphalt. Therefore, is this life cycle assessment limited to these materials. Other sources of emissions which contribute before, during or after the construction, like machinery, formwork, railings and electricity for lighting are not included.

It assumed the area of the bridge deck is the same for all the designs, therefore the pavement layer will also be the same. The technical data for the pavement is also collected from [72]. Since the pillars and footing are considered the same for all the bridge design, then the earthwork will also be the same and based on the technical data from the reference bridge design.

7.5.3.1 Reference design

The reference bridge design is based on Kjøkøysund bridge pre- report study. The bridge has the same dimensions and cross- section properties as the one in the report. The material for the reference bridge is assumed to be low carbon concrete class C, B45 M40/MF40 and 97% recycled steel reinforcement and tendons. In the report the quantities for cable tendons are given as $47\ 200\ mMN$ for the whole bridge. Since we perform the life cycle assessment only for the main span, we can reduce the tendons quantities in half. One Click LCA operates with the units $kg, ton\ and\ m^3$ for steel, then the unit mMN must be converted.

The equations for mMN in tendons are as following [77]:

$$f_y \sum_{i-1}^{n} L_i A_{si}$$

$where$:

$$f_y:\ steel\ quality\ in\ MPa, normally\ 1640\ MPa$$

$$L_i: Length\ of\ tendon\ times\ number\ of\ strands$$

$$A_{si}: Area\ of\ each\ strand, normally\ in\ Norway\ in\ either\ 140mm^2\ or\ 150mm^2$$

For the LCA the followings assumptions have been made regarding tendons properties:

$$Tendon\ force\ requirement: 23\ 600\ mMN$$

$$f_y: 1640\ MPa$$

$$L_i: 111\ 000\ mm\ x\ 25$$

$$A_{si}: 150mm^2$$

With the following assumption, it is necessary to have 35 tendons. The total volume for the steel tendons is $14{,}4\ m^3$.

The concrete and reinforcement quantities of respectively $5330\ m^3$ and $1066\ tons$ in the report are given for the whole bridge of 404 meters. By dividing the whole length with the length of the span, one gets the ratio which is 3,6727. The material quantities for concrete and reinforcement can be assumed by dividing the quantities of concrete and steel with the ratio number.

$$Concrete\ quantity: {}^{5330\ m^3}/_{3{,}6727} = 1451\ m^3$$

$$Reinforcement\ quantity: {}^{1066\ tons}/_{3{,}6727} = 290{,}24\ tons$$

7.5.3.2 Low carbon concrete

For the low carbon concrete design, the dimensions, cross section and steel quantities are assumed to be the same as the reference design, but the concrete material has been changed. Low carbon concrete class A and B are set as the one given in NB37 [78].
Since low carbon concrete has a slower strength development than regular concrete, then the casting process and formwork must stay longer in place before it can be removed. The strength development can be increased by adding X-seed [34]. Supplier of X-seed in Norway shows how concretes increases the strength development based of the content of X-seed. For both low carbon concrete class designs, it is assumed 2,5% of X-seed based on the cement weight of low carbon concrete class A. The cement content is set as 15% of the concrete volume.

7.5.3.3 HPC

From the literature study the cross section has been optimized and compared to have a lower material consumption than regular concrete hence the higher strength capacity. HPC has also better durability and the service life is appreciably double than regular concrete. Since it has not been calculated cross section capacity for Kjøkøysund bridge with HPC, a conservative assumption can be to split the material quantities in half from the regular concrete design. Since it is assumed, it will be necessary with two bridges of regular concrete to the fulfill the requirements over a 200 years' period compared to a bridge designed with HPC. The concrete strength in the life cycle assessments is set as C60/75.

7.5.3.4 Steel girder box

The design for the steel girder box is based on the dimensions and cross section of Randstandelva bridge. In the report the plate thickness varies between 15-40 mm. For the LCA it is assumed the thickness is 25 mm for the whole bridge. Both webs height is set as 5500 mm and the bottom flange width as 7000 mm. Total weight of the steel girder box, with a density of 7,85 ton/m^3 is 366 tons. Since the web height and plate thickness increases at the pillars, the weight has been increased by 20 %. The web height could be reduced if one utilizes a double composite bridge deck as mentioned in chapter 3.2.3. Since these types of bridges are more complex to calculate regarding capacity strength because of creep it is not used in Norway.

The weight for the steel in the steel box design is assumed to be 439,91 tons. The steel material for steel girder box design is 100% recycled steel.

The concrete for the bridge deck is set as low carbon class B with dimensions based on technical drawings. The volume of the concrete deck is $726\ m^3$. The steel girder box surface area of $1380{,}05\ m^2$ is painted with corrosion protection.

7.5.3.5 HSS

Literature study shows bridges with HSS can be designed with more slender plate thickness, hence reduce the total weight and material consumption. Assume the same design as for steel box girder bridge, but the overall plate thickness is 15 mm. From the literature study, it shows that it is difficult to get scrap based HSS because impurities, but the higher strength don't increase the emissions significantly. Therefor the steel for HSS is assumed to be 60% recycled S355 steel.

The weight of HSS, with the increase of 20% for varying plate thickness and web height at support, is 264,23 tons. It is assumed the same material and quantities for the bridge deck as for the steel girder box, concrete weight is therefore $726\ m^3$. The girder box for HSS is also painted with corrosion protection.

7.5.3.6 Timber arch and deck bridge design

The Oppstadåa bridge design is well suited for the main of Kjøkøysund bridge. With a traffic load of 16 500 vehicles a day, speed limit of 90 kilometers per hour and span length of 120 meters it meets the requirements for Kjøkøysund bridge.

For timber bridge design the material quantities are derived from the Oppstadåa timber bridge study. Both the arch and bridge deck are made up of glue laminated timber and the total quantities are $4701\ m^3$. The timber bridge design consists of steel hangers. For the LCA it is assumed scrap-based steel wires with an amount of 44,4 tons. There is also some reinforcement in the glue laminated deck. The quantities of reinforcement are 75 tons, and it is assumed 97% recycled steel.

In order for the timber bridge to reach a service life of 100 years it needs to be coated with protections. Mjøsa bridge had glue laminated timber quantities of $18500\ m^3$ with 100 tons of creosote. If we assume the same creosote density for Oppstadåa bridge, then it will contain 25 tons of creosote.

Technical data which is common for all bridge design:

Table 33: Common technical data for all the bridge designs

		Quantity	Unit
Earthwork	Gravel	140	m^3
Pillars and footing	Concrete B45 MF40	730	m^3
	Reinforcement B500C	146	$tons$
Pavement	Asphalt layer	Area: 1380 Thickness: 50	m^2 mm

Material inventory:

Table 34: Technical data for the different designs

Material	Unit	Reference design	Lowcarbon concrete A	Lowcabon concrete class A & B	High strength concrete	Steel girder box	High strength steel girder box	Timber arch truss and deck
Concrete class C	m^3	1451,23			-	726 (bridge deck)	726 (bridge deck)	-
Concrete class A	m^3	-	1451,23	725,14	-	-	-	-
Concrete class B	m^3	-	-	725,72	-	-	-	-
X-seed	$tons$	-	13	6,5	-	-	-	-
High strength concrete	$tons$	-	-	-	725,61	-	-	-
Steel	$tons$	-	-	-	-	439,91	-	44,4 (hanger s)
High strength steel	$tons$	-	-	-	-	-	264,23	-
Reinforcement	$tons$	290,24	290,24	290,24	145,12	-	-	75
Tendons	m^3	28,8	28,8	28,8	28,8	-	-	-
Glue laminated Timber	m^3	-	-	-	-	-	-	4701
Creosote	$tons$	-	-	-	-	-	-	25
Protective paint	m^2	-	-	-	-	1980	1980	-

8. Results and discussion

In this chapter, results from the case study on Kjøkøysund bridge, various calculations related to material and greenhouse gas emissions will be presented. It will also be discussed a more environmentally friendly solution of Kjøkøysund bridge, based on the results we have received.

8.1 EPD calculations stage A1-A3

8.1.1 Concrete B35 M45

The GWP for the concrete chosen is taken from the EPD's the distributors have provided. Figure 77 shows the GWP for stage A1-A4, from Vestfold Betong.

Miljøpåvirkning (Environmental impact)					
Parameter	**Unit**	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,04E+02	9,08E+00	4,51E+00	3,06E+00

Figure 77: Environmental impact for concrete B35 M45 (Vestfold Betong) [Appendix K]

To get the CO_2 emissions per meter for the main span, stage A1-A3 is added and then multiplied with the volume of the cross-section. Calculation is done in Microsoft Excel with this outcome:

Table 35: CO2 emissions calculated (Vestfold Betong)

Amount pr.m bridge		CO2-ekv		Total CO2
13,19	m^3/m	217,59	kgCO2/m^3	**2869,95 kg/m**

The same procedure is done with the other two distributors for the same type of concrete.

Miljøpåvirkning (Environmental impact)				
Parameter	**Unit**	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00

Figure 78: Environmental impact for concrete B35 M45 (Betong Øst) [Appendix G]

The volume is the same, but the changes are in the CO_2-eqv for their type of concrete. This gives a total CO_2 emission per meter at:

Table 36: CO2 emissions calculated (Betong Øst)

Amount pr.m bridge		CO2-ekv		Total CO2	
13,19	m^3/m	240,94	kgCO2/m^3	3177,93	kg/m

Miljøpåvirkning (Environmental impact)					
Parameter	**Unit**	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,31E+02	8,27E+00	4,76E+00	2,03E+00

Figure 79: Environmental impact for concrete B35 M45 (NorBetong) [Appendix I]

This EPD gives a total CO_2 emission per meter at:

Table 37: CO2 emissions calculated (NorBetong)

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	244,03	kgCO2/m^3	3218,687914	kg/m

The results above show how much CO_2 emissions the concrete has per meter, from different concrete suppliers. Table 35 shows a total CO_2 emission of 2869.95 kilograms per meter for concrete B35 M45 from Vestfold Betong. The EPD of Vestfold Betong gives CO_2-eqv to phases A1-A4. In this calculation, the equivalents in phases A1-A3 are added together and used as the final CO_2-eqv. Table 36 shows a total CO_2 emission of 3177.93 kg/m, which was expected to be higher than the concrete from Vestfold Betong due to GWP in the various phases. Finally, we see in Figure 37 that NorBetong accounts for the highest CO_2 emissions with 3218.69 kg/m. Betong Øst and Norbetong's concrete end up with significantly higher total CO_2 emissions because their concrete has a relatively higher GWP than the concrete of Vestfold Betong.

8.1.2 Combination of low carbon B and A

The other option is that the cross-section will consist of two parts, with two different types of low carbon concrete (type B and A). The bridge deck will be of low carbon B so that the casting time of the concrete will be accomplished before it can be applied the tendon cables. While the lower part of the cross-section will use low carbon A.

The calculation of the total CO_2 emissions when using low carbon B and low carbon A concrete from Vestfold Betong is shown in table 38.

Table 38: CO2 emissions calculated for low carbon A and B (Vestfold Betong)

Amount pr.m bridge		CO2-ekv		Total CO2	
B					
6,5975	m^3/m	217,59	kgCO2/m^3	1435,550025	kg/m
A					
6,59222	m^3/m	201,57	kgCO2/m^3	1328,794233	kg/m
			Total for Both	**2764,344258**	kg/m

The calculation of the total CO_2 emissions when using low carbon B and low carbon A concrete from Betong Øst is shown in table 39.

Table 39: CO2 emissions calculated for low carbon A and B (Betong Øst)

Amount pr.m bridge		CO2-ekv		Total CO2	
B					
6,5975	m^3/m	240,94	kgCO2/m^3	1589,60165	kg/m
A					
6,5922		203,48	kgCO2/m^3	1341,385378	kg/m
			Total for both	**2930,987028**	kg/m

The calculation of the total CO_2 emissions when using low carbon B and low carbon A concrete from NorBetong is shown in table 40.

Table 40: CO2 emissions calculated for low carbon A and B (NorBetong)

Amount pr.m bridge		CO2-ekv		Total CO2	
B					
6,5975	m^3/m	244,03	kgCO2/m^3	1609,987925	kg/m
A					
6,5922		196,36	kgCO2/m^3	1294,448756	kg/m
			Total for Both	**2904,436681**	kg/m

The tables above show the results when combining Low carbon B and Low carbon A, for the various concrete suppliers. The first column of the figures shows the volume of the bridge deck and the bridge box. Low carbon B is used in bridge deck, while the bridge box will be of low carbon A, so the different parts will have different CO_2-eqv. In the last column of the figures, you see the result for the total CO_2 emissions for each part, but also together. Here too, Vestfold Betong is the one with the least CO_2 emissions, but you can see that NorBetong has a lower CO_2-eqv for Low carbon A, which means that the total emissions are closer to Vestfold Betong than with the B35 M45. Since Low carbon B is used in bridge deck in this solution, the curing time has no bearing when choosing from the various suppliers. This is because Low carbon B from these suppliers achieves the desired strength needed before tendon cables. In other words, the curing time of Low carbon B is low enough for it to be used in a cantilever bridge without having to wait and use measures such as heating or additives.

8.1.2 Low carbon A

The third option done with these three distributors is done with the whole cross-section consisting of low carbon A.

Table 41: CO2 emissions calculated for low carbon A (Vestfold Betong)

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	201,57	kgCO2/m^3	**2658,652308**	kg/m

Table 42: CO2 emissions calculated for low carbon A (Betong Øst)

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	203,48	kgCO2/m^3	**2683,844678**	kg/m

Table 43: CO2 emissions calculated for low carbon A (NorBetong)

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	196,36	kgCO2/m^3	**2589,933856**	kg/m

The results show the total CO_2-emissions from Low carbon A of the three distributors. Betong Øst and Vestfold Betong has a similar result, due to similar CO_2-eqv from the EPD's. Norbetong gets the lowest CO_2-emissions at 2589 kg/m, which is a difference from the other two options. Where Vestfold Betong would be the option with the lowest CO_2-emissions, both for the concrete B35 M45 and for the combination of Low carbon B and A. When using only low carbon A, the calculations show NorBetong as the best option. The calculations above are done on only stage A1-A3, which means the location of distributors will have an impact on the final results. Even though NorBetong provides Low carbon A with the lowest CO_2-emission, it is not necessarily the best option. The reason for that is the casting time of the different concrete types from the distributors. To be able to use Low carbon A and at the same time does not lose valuable time while constructing the bridge the concrete need to achieve a certain firmness.

The documents sent to us from the different distributors show that Vestfold Betong's Low carbon A has a casting time which is approximately equal to their Low carbon B, which does not make any difference when it comes to the tendon cables. But for Betong Øst and NorBetong using their Low carbon A, could become a challenge. Their concrete has a casting time that exceeds the recommended limit by a couple of days. This will lead to a few challenges, like dead time for the workers that need to wait for the concrete firmness, which again leads to an increase of the financial side. This can be solved with an increase in resources or with an optimal progress plan. When talking about optimal progress plan, we mean to use the time planned on the project efficiently. While waiting for the concrete to cast in the main span, there are possibilities to work on the different spans of the bridge. If the plan is made so that, when the main span is creating dead time, they can work on the other spans or fundamental parts of the bridge. This could lower the dead time, but most likely not remove it. The solution to avoid this dead time, is to add substances like X-Seeds to the concrete so that the firmness could be achieved or use different methods to heat the concrete to lower the casting time. Both of these solutions will lead to a more expensive and demanding process. And also, more CO_2-emissions because X-seed also contributes to greenhouse gas emissions.

8.2 Stage A4

For stage A4 we have used a transport calculator provided by Østfoldforskning. The calculations have been done for all three distributors, with all three of them using the same method to transport the concrete. The differences are in the distance from factory to construction site, the weight of the different types of concrete and the different CO_2-eqv taken from the EPD's.

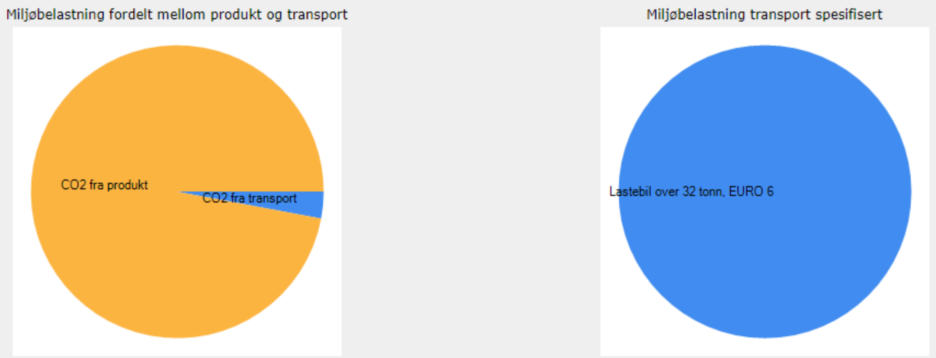
The result in stage A4 for concrete B35 M45 from Vestfold Betong is shown in figure 81.

Inn data

ID	Material	kg	CO_2-eq		Distanse type	Transport	km	Kommentarer		
3567	Betongelement	30586,97	217,59		Enkel	Lastebil over 32 tonn, EURO 6	83,00	Vestfold Betong		

Figure 80: Data input for concrete B35 M45 from Vestfold Betong in the transport calculator

Resultat Analysen



Detaljert resultat transport

Navn	km	GWP (kg CO_2-eq)	ODP (kg CFC11-eq)	AP (kg SO_2-eq)	EP (kg PO_4^{3-}-eq)	POCP (kg C_2H_4-eq)	ADPM (kg Sb-eq)	ADPE (MJ)
Lastebil over 32 tonn, EURO 6	83,00	210,0937	0,000043000	0,542321000	0,074796000	0,032866000	0,000500000	3449,0634
Totalt	83,00	210,0937	0,000043000	0,542321000	0,074796000	0,032866000	0,000500000	3449,0634

Figure 81: Results for concrete B35 M45 from Vestfold Betong done in transport calculator

The same calculation using the same transportation calculator is used on the other types of concrete with the other distributors also. Tables of the results from each scenario are presented below.

Table 44: Result of transportation CO2 emissions for all the distributors using concrete B35 M45

B35 M45	kg per m^3 of concrete	CO2 -eq	Distance (km)	Result GWP (kg CO2 - eq)
Vestfold Betong	30586,97	217,59	83	210,093
Betong Øst	32499,48	240,94	64,3	172,936
NorBetong	31839,99	244,03	107	281,939

Table 45: Result of transportation CO2 emissions for all the distributors using concrete Low carbon B and A

Low carbon B + A	Type of concrete	kg per m^3 of concrete	CO2 -eq	Distance (km)	Result GWP (kg CO2 - eq)	Total GWP
Vestfold Betong	Low carbon B	15299,6	217,59	83	105,0889	
	Low carbon A	15907	201,57	83	109,2612	214,3501
Betong øst	Low carbon B	16256,24	240,94	64,3	86,5027	
	Low carbon A	15821,33	203,48	63,3	84,1884	170,6911
NorBetong	Low carbon B	15926,37	244,03	107	141,0259	
	Low carbon A	15794,96	196,35	107	139,8624	280,8883

Table 46: Result of transportation CO2 emissions for all the distributors using concrete Low carbon A

Low carbon A	kg per m^3 of concrete	CO2 -eq	Distance (km)	Result GWP (kg CO2 - eq)
Vestfold Betong	31826,8	201,57	83	218,610
Betong Øst	31655,3	203,48	64,3	168,444
NorBetong	31602,6	196,35	107	279,837

Table 44 shows the end result for CO_2 emissions for concrete B35 M45 from the various concrete distributors in stage A4. The table shows how much CO_2 emissions there are per given amount of kg, over the distance from the factory to the construction site. One can see that the results are quite different, and there are several reasons for that. The weight of the concrete is somewhat different, the distance to the construction site and the CO_2-eqv to the concrete. Betong Øst ends up with the lowest emissions with 172,936 kg CO_2, even though it has a higher CO_2-eqv and the weight is higher. The reason for this is the distance from the factory to the construction site, which shows that how far you have to transport has a great impact on CO_2 emissions.

Table 45 shows the results for the combination of low carbon B and low carbon A from the various distributors. Here you can also see that when it comes to CO_2 emissions from transport, Betong Øst is the most environmentally friendly alternative. A difference in this result is that the concrete from Vestfold Betong has higher CO_2 emissions when there is a combination of the concrete, this is due to the weight of low carbon A which means that the total weight increases from the previous Table. Otherwise for the other concretes this was a slightly better result.

Table 46 shows that Betong Øst is the most environmentally friendly alternative in this case, and this is due to a shorter distance from the factory to the construction site. It has the lowest CO_2 emissions among all cases with 168.44 kg CO_2. In this case, Vestfold Betong has a higher CO_2 emission than the other two cases, the reason for this is that the weight of low carbon A is higher. NorBetong's distance makes it the one with the highest CO_2 emissions in every case.

Table 47: Total CO2 emissions from all distributors and different concrete types of stage A1-A4

Distributor and concrete type	B35 M45 CO2-emissions	Combination of Low carbon B and A CO2-emissions	Low carbon A CO2-emissions
Vestfold Betong	3080,04 kg/m	2978,69 kg/m	2877,26 kg/m
Betong Øst	3350,86 kg/m	3101,68 kg/m	2852,28 kg/m
NorBetong	3500,63 kg/m	3185,32 kg/m	2869,77 kg/m

Table 47 shows the total CO2-emissions when combining everything together, from the production stage to everything being on the construction site (stage A1-A4). The results show as expected, that when using low carbon A on the whole bridge cross-section we will get the lowest CO2-emissions. On the other hand, if choosing this option as said earlier in this thesis the challenges for casting time will occur. Vestfold Betong has a slightly higher CO2-emissions when using low carbon A, but at the same time their low carbon A has a desirable casting time when constructing a cantilever bridge. While the other two distributors will have to use substances like X-Seeds or use heating mats on the concrete to acquire the desirable casting time. For the combination of the two low carbon types, the option with the lowest CO2-emissions is Vestfold Betong and here the required casting time is not a challenge to acquire.

8.3 Steel girder alternative

In comparison, another GWP calculation has been made for a steel girder box with recycled steel. Three steel suppliers, the same mentioned in chapter 4.3.3.2, located in Europe have been analyzed and combined with low carbon concrete class B and A. Cross section dimensions and volume for one meter of the steel bridge superstructure are given in table 25.

Table 48: Dimensions and volume for 1 meter of steel bridge cross-section

	Tykkelse	dimensjon	lengde	volum i mm3	volum i m3	Densitet	Vekt i t	
flens	20	7000	1000	140000000	0,14	7,85	1,099	
steg h	20	5500	1000	110000000	0,11	7,85	0,8635	
steg v	20	5500	1000	110000000	0,11	7,85	0,8635	
						SUM	2,826	ton/m

Table 48 shows the result of greenhouse gas emissions, given as CO2- eqv, the steel has per meter, from three different steel distributors including the transport stage A4. The results show that MetaCon has the lowest CO_2 emissions with a total of 1,79 t/m. It can be seen in the results that the distance from the factory to the construction site plays a big role. Even though BGOUP had the lowest GWP, it ended up with the highest CO_2 emissions with a total of 3,57 t/m. The main reason for that is the distance is significantly higher than the other two distributors.

Table 49: Greenhouse gas emissions for the steel girder alternative

	Material	Material vekt per meter (t/m)	CO2-eqv (t/t steel)	Transport CO2-eqv (t)	Totalt utslipp (t/m)
Steel	BGROUP	2,826	0,518	0,748	3,577716
	Metacon	2,826	0,624	0,01231	1,79821206
	ALFA GROUP	2,826	0,684	0,04525	2,0608605

Table 49 shows the emissions result included the concrete bridge deck. For the bridge decks there where two alternatives, one with low carbon concrete class B and the second one with class A. Since the concrete quantity is the same for all three designs, the results are the same as in table 48 with steel from MetaCon which has the least emissions.

Table 50: Greenhouse gas emissions for the steel girder alternative with concrete deck

		Totalt utslipp uten dekke	Lavkarbon B	Totalt utslipp med dekke B	Lavkarbon A	Totalt utslipp med dekke A
Steel	BGROUP	3,577716	1,435550025	5,013266025	1,329858075	4,907574075
	Metacon	1,79821206	1,435550025	3,233762085	1,329858075	3,128070135
	ALFA GROUP	2,0608605	1,435550025	3,496410525	1,329858075	3,390718575

Table 51: greenhouse gas emissions from the concrete deck

Material	Mengde per meter bru (m3/m)	CO2-eqv (kg/m3)	Totalt (t/m)
Lavkarbon B	6,5975	217,59	1,435550025
Lavkarbon A	6,5975	201,57	1,329858075

When comparing the result with the result we got from using concrete, the box girder alternative will lead to more emissions except for the case where low carbon concrete class B from Betong Øst and NorBetong. Then the steel from MetaCon and Alfa GROUP can provide a more environmentally bridge design alternative, which means that it could still be a suitable alternative for the Kjøkøysund bridge.

8.4 Life cycle assessment

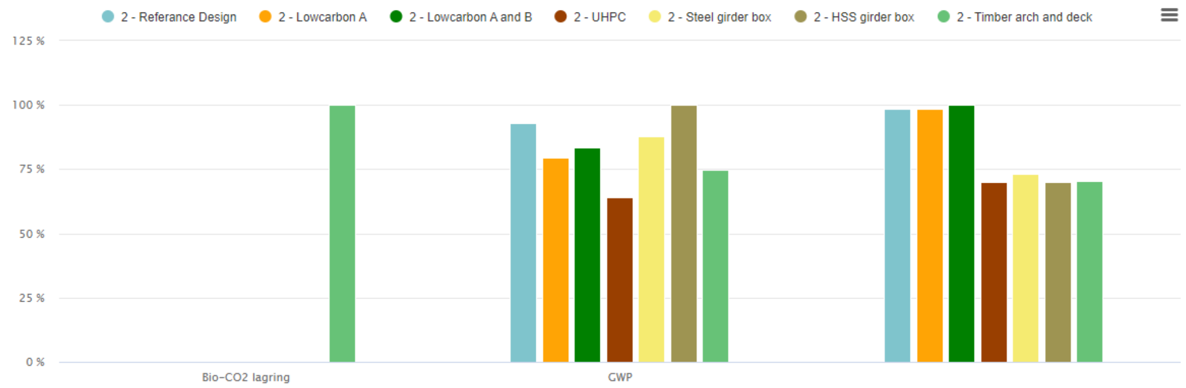
The results from the life cycle assessment of the bridge designs are shown in figure 82. For all the design it is clearly material production stage, A1-A3, that contributes significantly to the emission. The second highest emissions come from transportation except for the timber bridge design.

The reference bridge design has the second most global warming potential with 92%. The HSS bridge design had the most global warming impact. Both low carbon concrete designs had lower global warming impact than the steel box girder design. The design with the lowest global warming impact was the high-performance concrete and glue laminated timber bridge with respectively 63% and 74%.

The furthest right chart in figure one below shows the material quantities for each bridge design by weight in tone. It is clear that concrete design, except for UHPC, have the most material consumption. The steel and glue laminated timber designs have approximately the same quantities of material.

Figure 83 shows the CO_2-equivalents of greenhouse gas emissions in tons. The HSS design has the highest emission in the production stage with 1222 tons, followed by the reference bridge design with 1091 tons. The steel box girder, low carbon concrete A and B, and low carbon concrete A design have emissions of respectively 1059 ton, 972 tone and 922 tone. The lowest emission in the production stage comes from the timber bridge design with an emission of 634 tone. The transportation stage for the design varies from 29 tons $CO_2 - eqv$ to 51 tones $CO_2 - eqv$.
All the concrete designs had benefits of carbonization of cement through the lifetime period but is negligible.

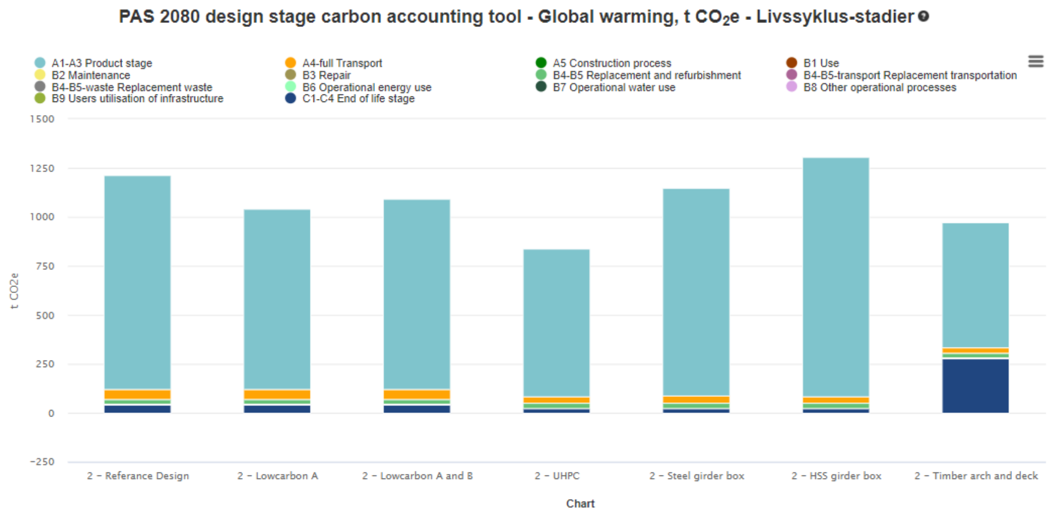
The replacement and refurbishment stage contributes 25 tons $CO_2 - eqv$ for all the bridge designs. For end-of-life stage emissions vary between 20 to 40 tons except for the timber bridge design which has an emission of 278 tons.



Chart

Category	2 - Referance Design	2 - Lowcarbon A	2 - Lowcarbon A and B	2 - UHPC	2 - Steel girder box	2 - HSS girder box	2 - Timber arch and deck
Bio-CO2 lagring	0	0	0	0	0	0	100
GWP	92.77157230179476	79.46126676664421	83.37689584389216	63.964223740913596	87.70658695743265	100	74.68406518888891
	98.32606525574619	98.32606525574619	100	69.88809661040436	73.01016749977889	70.19943593851247	70.47799789874955

Figure 82: Life cycle assessment results from One Click LCA which shows GWP and material weights



Category	A1-A3 Product stage	A4-full Transport	A5 Construction process	B1 Use	B2 Maintenance	B3 Repair	B4-B5 Replacement and refurbishment	B4-B5-transport Replacement transportation	B4-B5-waste Replacement waste	B6 Operational energy use	B7 Operational water use	B8 Other operational processes	B9 Users utilisation of infrastructure	C1-C4 End of life stage
2 - Referance Design	1091.1122676849034	51.268064951929276	0	-0.03528	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	43.07071645604251
2 - Lowcarbon A	922.2793859546514	51.54202381645358	0	-0.03528	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	43.106196116691876
2 - Lowcarbon A and B	972.4676906173222	52.00507845037359	0	-0.03528	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	43.0928546254904
2 - UHPC	752.2054566886143	35.01088218212479	0	-0.0315	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	21.75650343074491
2 - Steel girder box	1059.9689423191708	35.888373708538786	0	0	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	23.36570887020339
2 - HSS girder box	1222.8595820817786	35.10250620756419	0	0	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	21.91979137020339
2 - Timber arch and deck	634.7574507325442	29.738718430057784	0	0	0	0	25.659862771139945	0	1.3276697116848946	0	0	0	0	278.7972129999147

Figure 83: Results of GWP for the different stages

As expected, based on the literature study, the reference bridge has a high emission compared to the other design. Even though both low carbon concrete designs are based on the same bridge as the reference bridge, the emissions are lower for both designs. This comes from the lower cement contents in the concrete which impacts the emissions.

UHPC with concrete C60/75 have the lowest emissions. This result comes from the reduced material quantities. From the literature study, UHPC has better durability compared to regular concrete and therefore will probably have an extended service life under the same circumstances. Since UHPC has better material properties, the cross section can be optimized and reduce the concrete consumption. Since this thesis is limited to literature study, conservative assumption was made regarding the UHPC content. In the life cycle assessment, the service life is considered to be 100 years for all the bridge designs, but UHPC has better durability and is assumed to have a service life of 200 years. Therefore, the concrete material consumption for UHPC was divided in two to be able to compare the emission with the other design based on a 100- years period.

The steel box girder bridge has a lower emission compared to the reference bridge, but worse than both the low carbon concrete design alternatives. This is due to the high emission from the steel manufacturing event though the steel is 97% scrap based. The results from the steel girder box are open for discussion since the design is based on Ranstadelva bridge, which has almost the same span as Kjøkøysund bridge. To get an even more realistic result then it must be projected a steel box girder specifically for Kjøkøysund and then do a life cycle assessment based on that model. The assumptions made for the steel bridge design will also influence the results. The steel material quantities are calculated based on the plate thickness and global dimension of the superstructure of the bridge.
The thickness of the plate and height of webs will increase in order to withstand the negative moments which occur at the pillars. Since it was not possible to get the cross-section blueprints for Randstadelva bridge, the steel quantities are increased by 20% to compensate for the variety of the plate thickness and web height.

The literature study showed that for HSS it is possible to reduce the material quantities and self-load by reducing the plate thickness compared to regular steel for the same bridge design. Therefore, in the life cycle assessment the plate thickness was reduced from 25 mm to 15 mm compared to the steel box girder design. The literature study showed also there is lack of scrap based HSS because of impurities and therefore the steel material was changed from 97% scrap based to 60% recycled steel. With these assumptions the HSS bridge design the highest emissions. As for regular steel design, the results from the assessment for HSS design are open for discussion. Since HSS has better material properties compared to regular steel, the cross section can be reduced and optimized which in order will give a lighter structure. By optimizing the cross section, it is able to reduce the material quantities. In this life cycle assessment, the HSS bridge design is based on Randstadelva bridge, but with the assumption of thinner steel plates. If the box girder was projected and optimized specifically for Kjøkøysund then the emission results might be different.

The second lowest emission comes from the glue laminated timber bridge design. The design is based on the study for Oppstadåa bridge with timber arch and deck. The bridge span of 120 meters is suitable for the main span of Kjøkøysund bridge. Since timber has low self-weight, it also has the lowest transport emission in the life cycle assessment. Timber stores CO_2 and these will be released when it is burned after its service purpose. That is why glue laminated timber has the highest emission in the end-of-life stage.

8.5 Further discussion

The handbook *Prosesskode 2* [29] says for bridges the concrete must be in durability class MF45. If the handbook regulates to utilize other concrete types for constructions where the risk of chloride attacks, then it is possible to reduce the emissions [55]. An example would be bridges which are not water crossing bridges, like highway crossing bridges. This would although give the contractors more responsibility and the road authority must trust the calculations made by the projecting firm [55].

Concrete is a cheap material compared to steel and timber as a construction material, therefore there are many bridges made of concrete. Regular concrete like B35/45 MF40/45 is very standardized and therefore there are many suppliers. When it comes to low carbon concrete, then it is a relatively new concrete type. During the work with this thesis, the authors were not able to find any bridges constructed with low carbon concrete class A or better. If any contractor had constructed or experience with bridges utilizing low carbon concrete, then they would probably brag about it since reducing emissions is a very hot theme and everybody tries to compete to reduce their carbon emissions.

The authors have also been in contact with cement and concrete suppliers and asked if they had delivered low carbon concrete for bridge projects, but none of them had since it was not demanded by the contractors. The contractor's main motive is to earn profit, and if the consequence of using low carbon concrete is reduced earning or losing money on the project then they will of course not show interest in using low carbon concrete. Changes and trends in the industry often start with demands from the big construction clients [79].

Almost every bridge is owned by the state [80] and they set the requirements for the bridge constructions. In order to move the bridge industry into a more environmentally direction then the state must value emission reduction as one of the highest criteria in tender processes. An example of where a big client demand has shifted the industry is emissions free constructions sites [81]. In order to be able to compete in tender processes for building projects for a local agency in Norway, *Oslo kommune*, then one must be an emissions free contractor at the building site. This could be implemented on a national plan and hence change the industry national wide.

From the literature study, it shows that there are not any obstacles for utilizing low carbon concrete in bridges. The slower strength development can be reduced significantly by using X- seed or combining different low carbon concrete classes, but this would increase the cost.

Therefore, should public clients take the cost and demand using low carbon concrete where it is possible since the state will gain benefits in the long run if low carbon concrete is used commercially by moving the industry into a more environmentally path.

High performance concrete is another interesting direction in order to become more environmental. Even though the concrete contains a higher cement content which leads to a higher emission, it will gain benefits such as better durability. The literature study shows that the service life can be extended from 100 years for normal concrete to 200 years for high performance concrete. Since high performance concrete has a higher compression strength, the structure can also be optimized and hence reduce the material quantities. This combination is interesting since emissions from the production stage might be higher than for normal concrete but accounted for the whole service life span then the high-performance concrete has a lower emission. Since there are no existing bridges of high-performance concrete which have been around for 200 years, there is little study and study of the durability and real-life service life on high performance concrete. Therefore, more study must be carried out, especially for bigger constructions like Kjøkøysund bridge.

Glue laminated timber in bridges have been used in Norway for a long time, but spans have been limited to 80 meters. For longer spans, concrete is cheaper and therefore is the preferred choice. The main concern when it comes to glue laminated timber is the service life capacity. From the literature study, the most important factor for glue laminated timber is the moisture content. If it can be kept to a minimum throughout the service life, then a service life of 100 years is achievable.

9. Conclusion and further research

The increased focus on global warming and greenhouse gas emissions has prompted new solutions in the constructions industry, which produces significant emissions. The savings potential is huge, and study in this area is currently underway. Low-carbon concrete is an option with a lot of potential, notably in the concrete element sector. The world can save substantial amounts of greenhouse emissions if low carbon concrete is a requirement in projects where it can be utilized.

Calculations regarding greenhouse gas emissions has been carried out for three different bridge cross-sections designs with concrete from three concrete distributors located in Norway. This gave nine different scenarios, giving us a broad picture to choose from. Regarding greenhouse gas emissions, the lowest result was from Betong Øst using their low carbon A concrete. While Vestfold Betong was the distributor with the lowest emissions on average for the three options. The low carbon A from Betong Øst is the one with the lowest emissions, the option from Vestfold Betong is most likely the best overall alternative. This is because of the casting time, Vestfold Betong has developed a low carbon concrete class A with satisfying casting time needed to use for a balanced cantilever concrete bridge as needed for Kjøkøysund bridge. Betong Øst and NorBetong would need substances like X-Seeds or heating mats on the concrete to get the required compression strength capacity before adding tendon cables.

When using concrete B35 M45 or a combination of low carbon A or B on the bridge, showed an increase in the CO_2-emissions compared to the alternative with only low carbon A. But if considering using NorBetong or Betong Øst, combining the two low carbon classes would be a better option than only using low carbon A. The reason for that is the shortened casting time for the concrete. From research we have concluded that the combination of low carbon concrete in a cantilever bridge is possible, but it needs further research and incentives from the state so that it can be done in practice to be able to establish this.

There have also been EPD calculations for three steel bridge alternatives. There are also here three distributors from three different locations in Europe. The same transport calculator is used in this calculation. The total greenhouse gas emission from the different stages A1-A4 has been calculated and the result shows that steel box girder with recycled steel in combination with a concrete deck had a higher greenhouse gas emissions than low carbon concrete designs. Compared to concrete B35 M45, the recycled steel had lower emissions for two out of the three distributors.

Based on the span and traffic load for Kjøkøysund bridge, seven other bridge designs have been considered in the case study for the new Kjøkøysund bridge.
The life cycle assessment, which was performed in the software One Click LCA, showed the high-performance concrete had the best emissions followed by the glue laminated timber bridge design. Both low carbon concrete designs had better emissions than the steel alternatives and the reference bridge. The design with high strength steel had the highest emissions.

The results for high performance concrete and non-concrete designs must be further evaluated since they are based on the literature study and not specially projected and optimized for

Kjøkøysund bridge. It has also not been done any calculations regarding the cross-section capacity, since the work would require a whole thesis itself.

Regarding high performance concrete and glue laminated timber bridges with span length greater than 80 meters, there is little research. The main advantage of high-performance concrete is better durability and extended service life, but more research must be conducted before it can be commercially accepted. Some preliminary projects regarding Oppstadåa bridge and Mjøsa bridge show it is able to construct long span glue laminated timber bridges.

Based on the literature study and the results from the life cycle assessment in this thesis it is possible to reduce the emissions for the new Kjøkøysund bridge.

The main reason which contractor don't use low carbon concrete is the longer time regarding the strength development. This will lead to a higher cost which is not in the interest of the contractors. There are solutions regarding the slower strength development. Large span bridges are public owned and therefore the additional cost must be covered by the state in order to move the industry into a more environmentally path.

References

[1] Hunton, "trebaserte byggematerialer bidrar til mindre klimagassutslipp," 2022. [Online]. Available: https://www.hunton.no/hvorfor-hunton/karbon-fotavtrykk/. [Accessed 2022].

[2] L. Hök and S. Smedley, "Co-creating solution to reduce the industry's carbon footprint," 25 November 2019. [Online]. Available: https://group.skanska.com/media/articles/co-creating-solutions-to-reduce-the-industry-s-carbon-footprint/. [Accessed 2022].

[3] National Geopgraphic, "Effect of global warming," 2022. [Online]. Available: https://www.nationalgeographic.com/environment/article/global-warming-effects. [Accessed 2022].

[4] Center for Sustainable Systems, University of Michigan, "Greenhouse Gases Factsheet," September 2021. [Online]. Available: https://css.umich.edu/sites/default/files/Greenhouse%20Gases_CSS05-21_e2021_0.pdf. [Accessed 2022].

[5] A. K. Lassen, "MABY4300- Sustainability Assessment and Life Cycle Analysis," OsloMet, Oslo, 2020.

[6] EuropeanCommission- Joint Research Centre, "Life Cycle Thinking and Assessment," November 2011. [Online]. Available: https://web.archive.org/web/20111112081845/http://lct.jrc.ec.europa.eu/ . [Accessed 2022].

[7] S. Kittelberger, "What is a Life Cycle Assessment?," 14 April 2020. [Online]. Available: https://www.circular-flooring.eu/news/what-is-a-life-cycle-assessment/. [Accessed 2022].

[8] Standard Norge, "Miljøstyring- Livsløpsvurdering- Prinsipper og rammeverk (ISO 14040:2006)," Standard Norge, 2006.

[9] Shaun, "Life Cycle Stages," 2022. [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360015064999-Life-Cycle-Stages. [Accessed 2022].

[10] LCA, "Hva er EPD?," 2022. [Online]. Available: https://lca.no/hva-er-epd/. [Accessed 2022].

[11] D. Askeland, "B30 M60 22mm Lavkarbon kl.A LB302560," 2020. [Online]. Available: https://www.epd-norge.no/getfile.php/1319568-1625832054/EPDer/Byggevarer/Ferdig%20betong/NEPD-2963-1654_B30-M60-22mm-Lavkarbon-klA-LB302560.pdf. [Accessed 2022].

[12] W. Lin and T. Yoda, "Bridge Engineering," 2017. [Online]. Available: https://www.sciencedirect.com/book/9780128044322/bridge-engineering. [Accessed 2022].

[13] B. Terranova, R. Desroches and A. Shafieezadeh, "Analaytical Frangility Assessment of an Isolated Multi- Span Simply Supported Concrete Girder Bridge in Moderate Seismic Zones," September 2012. [Online]. Available: https://www.researchgate.net/publication/281177083_Analytical_Fragility_Assessment_of_

an_Isolated_Multi-Span_Simply_Supported_Concrete_Girder_Bridge_in_Moderate_Seismic_Zones/link/55d9ea6108aec156b9ae6ff4/download. [Accessed 2022].

[14] midas Bridge, "Arch Bridge," [Online]. Available: https://www.midasbridge.com/en/solutions/arch-bridges. [Accessed 2022].

[15] Historic Bridge FOUNDATION, "BRIDGE TYPES," [Online]. Available: https://historicbridgefoundation.com/bridge-types/. [Accessed 2022].

[16] D. B. Billington, "bridge engineering," [Online]. Available: https://www.britannica.com/technology/bridge-engineering. [Accessed 2022].

[17] I. Vayas and A. Iliopoulos, Design of Steel- Concrete Composite Bridges to Eurocodes, Taylor & Fracis Group, 2014.

[18] J. Brozzetti, "Design development of steel- concrete composite bridges in France," July 2000. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0143974X99000875#BIB9. [Accessed 2022].

[19] S. L. Stroh and R. Sen, "Steel Bridges with Double- Composite Action: Innovative Design," January 2000. [Online]. Available: https://www.researchgate.net/publication/245559131_Steel_Bridges_with_Double-Composite_Action_Innovative_Design . [Accessed 2022].

[20] Krishna, "Different Types of Bridges | Bridge % its components," March 2022. [Online]. Available: https://civilread.com/different-types-of-bridges/. [Accessed 2022].

[21] Lokalhistoriewiki, "Tromsøbrua," Norsk lokalhistorisk institutt, 2022. [Online]. Available: https://lokalhistoriewiki.no/wiki/Troms%C3%B8brua. [Accessed 2022].

[22] midas Bridge, "Balanced Cantilever Bridges," 2022. [Online]. Available: https://www.midasbridge.com/en/solutions/balanced-cantilever-bridges. [Accessed 2022].

[23] Kontrollrådet, "Betongens historie," March 2018. [Online]. Available: https://kontrollbetong.no/aktuelt/betongens-historie/. [Accessed 2022].

[24] PCA- America'a Cement Manufacturers , "How Concrete is Made," [Online]. Available: https://www.cement.org/cement-concrete/how-concrete-is-made. [Accessed 2022].

[25] Sintef- Byggforskserien, "Tilsetningsstoffer for betong," September 2010. [Online]. Available: https://www.byggforsk.no/dokument/590/tilsetningsstoffer_for_betong#i11. [Accessed 2022].

[26] HexAmor, "Your skin on concrete: Irritation, burns, and dermatitis," October 2020. [Online]. Available: https://www.hexarmor.com/posts/concrete-irritation-burns-and-dermatitis. [Accessed 2022].

[27] R. Maddalena, J. J. Roberts and A. Hamilton, "Can Portland cement be replace by low-carbon alternative materials? A study on the thermal properties and carbon emissions of

innovative cements," June 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652618304505?via%3Dihub#appsec1. [Accessed 2022].

[28] Dynamic Concrete Pumping, "Different Types of Concrete," March 2020. [Online]. Available: https://www.dcpu1.com/blog/different-types-of-concrete/. [Accessed 2022].

[29] Statens vegvesen, "Prosesskode 2- Standard beskrivelse for bruer og kaier," June 2018. [Online]. Available: https://www.vegvesen.no/globalassets/fag/handboker/hb-r762-prosesskode-2-05072018.pdf. [Accessed 2022].

[30] Norsk Betongforening, "37 PDF LAVKARBONBETONG," 2020. [Online]. Available: https://betong.net/nettbutikk/nb-publikasjoner/37-pdf-lavkarbonbetong-2015-gratis-nedlasting-klikk-les/. [Accessed 2022].

[31] Statens Vegvesen, "Bruprosjektering- Prosjektering av bruer, ferjekaier og andre bærende konstruksjoner," April 2015. [Online]. Available: https://www.vegvesen.no/globalassets/fag/handboker/hb-n400-bruprosjektering.pdf. [Accessed 2022].

[32] Standard Norge, "NS-EN 13670:2009+NA:2010- Utførelse av betongkonstruksjoner," October 2010. [Online]. Available: https://www.standard.no/no/nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=447619. [Accessed 2022].

[33] NORCEM, "Herdeteknologi," [Online]. Available: https://www.norcem.no/sites/default/files/assets/document/bb/11/herdeteknologi_lav.pdf. [Accessed 2022].

[34] MASTER BUILDERS SOLUTIONS, "Master X-seed STE- Unikt herdeakselerende tilsetningsstogg til lavkarbon betong," September 2021. [Online]. Available: https://assets.master-builders-solutions.com/nn-no/mbs_brochure_master_x-seed_ste_no.pdf. [Accessed 2022].

[35] Sintef- Byggforskserien, "Betong. Typer, egenskaper og bruksområder," March 2016. [Online]. Available: https://www.byggforsk.no/dokument/5157/betong_typer_egenskaper_og_bruksomraader#i5. [Accessed 2022].

[36] S. K. Neenu, "Normal Concrete cs. High- Strength Concrete Properties and Difference," [Online]. Available: https://theconstructor.org/concrete/normal-high-strength-concrete-properties/17771/. [Accessed 2022].

[37] M. I. Hamakareem, "Application of High- Performance Concrete in Civil Engineering," [Online]. Available: https://theconstructor.org/concrete/high-performance-concrete-applications/38819/. [Accessed 2022].

[38] nature, "Concrete need to lose its colossal carbon footprint," September 2021. [Online]. Available: https://www.nature.com/articles/d41586-021-02612-5. [Accessed 2022].

[39] D. Wimpenny, "ow Carbon Concrete Option for the Next Generation of Infrastructure," January 2009. [Online]. Available: https://www.researchgate.net/publication/242155430_Low_Carbon_Concrete_-_Options_for_the_Next_Generation_of_Infrastructure. [Accessed 2022].

[40] K. M. Eriksen, "1 M3. B35 M45- N4350- Lavkarbon B," 2020. [Online]. Available: https://www.epd-norge.no/getfile.php/1315928-1604488490/EPDer/Byggevarer/Ferdig%20betong/NEPD-2508-1250_B35-M45---N4350---Lavkarbon-B.pdf. [Accessed 2022].

[41] J. Nøsavik, "Ferdigbetong B35 M45 D22," 2020. [Online]. Available: https://www.epd-norge.no/ferdig-betong/ferdigbetong-b35-m45-d22-article2943-317.html. [Accessed 2022].

[42] E.-. aim, "1.2 Reinforced concrete vs Prestressed concrete," 2021. [Online]. Available: https://www.youtube.com/watch?v=HuroccOxDfM. [Accessed March 2022].

[43] SSAB, "CO2 efficient steel production," [Online]. Available: https://www.ssab.com/en/company/sustainability/sustainable-operations/co2-efficiency. [Accessed 2022].

[44] H. Medarac, J. A. Moya and J. Somers, "Production cost from iron and steel industry in the EU and third countries," 2020. [Online]. Available: https://www.eurofer.eu/assets/news/eu-technical-report-on-production-costs-from-the-iron-and-steel-industry-in-the-eu-and-third-countries/production_costs_from_the_iron_and_steel_industry_-_final_online.pdf. [Accessed 2022].

[45] NORSK STÅL, "Stålproduksjon i dag," [Online]. Available: https://www.norskstaal.no/om-oss/miljoe-og-baerekraft/staalproduksjon-i-dag. [Accessed 2022].

[46] Z. Qi, "A bottom-up Energy Effiency Improvement Roadmap for China's Iron and STeel Industry up to 2050," October 2016. [Online]. Available: https://www.researchgate.net/publication/316684889_A_Bottom-up_Energy_Efficiency_Improvement_Roadmap_for_China's_Iron_and_Steel_Industry_up_to_2050. [Accessed 2022].

[47] BELLONA, "Steel and emissions: How can we break the link?," March 2019. [Online]. Available: https://bellona.org/news/ccs/2019-03-is-steel-stealing-our-future. [Accessed 2022].

[48] A. Toktarova, I. Karlsson, J. M. Rootzén and L. Göransson, "Pathways for Low- Carbon Transition of the Steel Industry- A Swedish Case Study," July 2020. [Online]. Available: https://www.researchgate.net/publication/343249325_Pathways_for_Low-Carbon_Transition_of_the_Steel_Industry-A_Swedish_Case_Study.

[49] C. Swalec and C. Shearer, "Pedal to the Metal- NO TIME TO DELAY DECARBONIZING THE GLOBAL STEEL SECTOR," June 2021. [Online]. Available: https://globalenergymonitor.org/wp-content/uploads/2021/06/Pedal-to-the-Metal.pdf. [Accessed 2022].

[50] M. M. Jenssen, "IHULT- Luxembourg," 2019. [Online]. Available: https://www.epd-norge.no/getfile.php/1311525-1572904390/EPDer/Byggevarer/St%C3%A5lkonstruksjoner/NEPD-1913-839_IHULT---Luxembourg.pdf. [Accessed 2022].

[51] TATA STEEL, "The future is circular," [Online]. Available: https://www.tatasteeleurope.com/sustainability/circular-economy. [Accessed 2022].

[52] C. Venås, "Reinforcement steel products," 2019. [Online]. Available: https://www.epd-norge.no/getfile.php/1314271-1594379045/EPDer/Byggevarer/St%C3%A5lkonstruksjoner/929_Reinforced-steel-products-from-B-Group_en_1_1%281%29.pdf. [Accessed 2022].

[53] ACCIAIERIE DI SICILIA, "ENVIRONMENTAL PRODUCT DECLARATION FOR HOT- ROLLED REINFORCING STEEL FOR CONCRETE IN BARS AND COIL," March 2011. [Online]. Available: https://portal.environdec.com/api/api/v1/EPDLibrary/Files/48f48b1e-b890-4241-82b3-cb5b119d6e4d/Data. [Accessed 2022].

[54] TransMetal, how many times can scrap be recycled?, July 2019. [Online]. Available: https://transmetal.co.uk/how-many-times-can-scrap-be-recycled/. [Accessed 2022].

[55] Statens Vegvesen, "Bærekraftige betongkonstruksjoner- Reduksjon av klimagassutslipp ved bygging av Statens Vegvesen betongkonstruksjoner," December 2017. [Online]. Available: https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/2670333. [Accessed 2022].

[56] I. L. Larsen, "Determining the Environmental Benefits of Ultra High Performance Concrete as a Bridge Construction Material," 2017. [Online]. Available: https://iopscience.iop.org/article/10.1088/1757-899X/245/5/052096/pdf. [Accessed 2022].

[57] Norwegian Ministry of Transportation and Communications, "National Transport Plan 2018-2029," [Online]. Available: https://www.regjeringen.no/contentassets/7c52fd2938ca42209e4286fe86bb28bd/en-gb/pdfs/stm201620170033000engpdfs.pdf. [Accessed 2022].

[58] U.S. Department of Transportation, "Ultra- High Performance Concrete: A State-of-Art Report for the Bridge Community," June 2013. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/26387/dot_26387_DS1.pdf?. [Accessed 2022].

[59] N. Randl, T. Steiner, S. Ofner, E. Baumgartner and T. Mészöly, "Development of UHP mixtures from an ecological point of view," September 2014. [Online]. Available: https://www.researchgate.net/publication/263319370_Development_of_UHPC_mixtures_from_an_ecological_point_of_view. [Accessed 2022].

[60] S. Mitrovic, D. Popvic, M. Tepavcevic and D. Zakic, "Physical- mechanical properties and durability of ultra- high performance concrete (UHPC)," June 2021. [Online]. Available: https://www.researchgate.net/publication/352880595_Physical-mechanical_properties_and_durability_of_ultra-high_performance_concrete_UHPC. [Accessed 2022].

[61] The International Panel on Climate Change, "CLIMATE CHANGE 2077- MITIGATION OF CLIMATE CHANGE," 2007. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg3_full_report-1.pdf. [Accessed 2022].

[62] G. Habert, D. Arribe, T. Dehove, L. Espinasse and R. L. Roy, "Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges," 2012. [Online]. Available: https://zh.booksc.eu/book/16959904/88d90c. [Accessed 2022].

[63] BuilderSpace, "4 Types of Steel Used in Bridges," [Online]. Available: https://www.builderspace.com/types-of-steel-used-in-bridges. [Accessed 2022].

[64] G. Du and R. Karoumi, "Environmental life cycle assessment comparison between two bridge types: reinforced concrete bridge and steel composite bridge," July 2013. [Online]. Available: https://www.researchgate.net/publication/265776584_Environmental_life_cycle_assessment_comparison_between_two_bridge_types_reinforced_concrete_bridge_and_steel_composite_bridge. [Accessed 2022].

[65] Multiconsult, "FORSLAG TIL DETALJREGULERING- Prosjek: E16. Forprosjekt Randselva bru stålkassealternativ," December 2013. [Online]. Available: https://www.vegvesen.no/globalassets/vegprosjekter/utbygging/e16nymoenolum/vedlegg/vedtatt-plan-e16-eggemoen-olum/randselva-bru-stalkasse-forprosjekt.pdf . [Accessed 2022].

[66] M. S. Lemma, H. Gervásio, J. O. Pedro, C. Rigueiro and L. S. d. Silva, "Echancement of the life-cycle performance of bridges using high- strength steel," March 2019. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/15732479.2019.1662067. [Accessed 2022].

[67] J. O. Sperle and L. Hallberg, "ENVIRONMENTAL ADVANTAGES OF USING HIGH STRENGTH STEEL," [Online]. Available: http://www.sperle.se/referenser/pdf/artiklar/05_environmental.pdf. [Accessed 2022].

[68] THE INTERNATIONAL MOLYBDENUM ASSOCIATION, "High- strength steel- sustainable and money saving," January 2013. [Online]. Available: https://www.imoa.info/download_files/molyreview/excerpts/13-1/High_strength_steel.pdf. [Accessed 2022].

[69] R. O'Born and K. Vertes, "Comparative life cycle assessment of concrete and timber road bridge deck designs," June 2017. [Online]. Available: https://www.researchgate.net/publication/316645136_Comparative_life_cycle_assessment_of_concrete_and_timber_road_bridge_deck_designs. [Accessed 2022].

[70] R. O'Born, K. Vertes, G. Pytten, L. O. Hortemo and A. Brændhagen, "Life cycle assessment of an optimized network arch highway bridge utilizing timber," June 2017. [Online]. Available: https://www.researchgate.net/publication/316644962_Life_cycle_assessment_of_an_optimized_network_arch_highway_bridge_utilizing_timber/link/59fa4a590f7e9b61546eb38f/download. [Accessed 2022].

[71] R. O'Born, "Life cycle assessment of large scale timber bridges: A case study from the world's longest timber bridge design in Norway," March 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920917304339?casa_token=tdRV8cWrRyIAAAAA:bwRjvhCL_5DYhRnYqpa3OVB_z5pOU1vhTlep-I09mSgak8d1b8FElQVruoPf2aYgOjwh8jmRzw. [Accessed 2022].

[72] T. Valnes, "Fylkesvei 108- Ny Kjøkøysund bru. Forprosjekt for 01- 1163 Kjøkøysund," July 2020. [Online]. Available: https://viken.no/_f/p1/i6d70d1bc-665f-4208-a11b-151b22a23ca1/01-forprosjekt-ny-kjokoysund-bru.pdf. [Accessed 2022].

[73] Y. Aartun and T. Valnes, "Fv. 108- Ny Kjøkøysund bru- Skisseprosjekt," April 2019. [Online]. Available: https://viken.no/_f/p1/i80ac3762-8cd5-4ab3-96f0-8ae1b9c8dc2f/vedlegg-1-fv-108-ny-kjokoysund-bru-skisseprosjekt.pdf. [Accessed 2022].

[74] VEIER24, "Svinesundbrua kan være nedbetalt allerede til neste år," June 2019. [Online]. Available: https://www.veier24.no/artikler/svinesundbrua-kan-vaere-nedbetalt-allerede-til-neste-ar/466985. [Accessed 2022].

[75] Shaun, "General Infrastructure LCA Guidance," 2021. [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360014993380-General-Infrastructure-LCA-Guidance. [Accessed 2022].

[76] Shaun, "End of Life Scenarios for Construction Products," 2021. [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360015064959-End-of-Life-Scenarios-for-Construction-Products. [Accessed 2022].

[77] Spennarmering.blogspot.com, "Spennarmering i Norge," August 2013. [Online]. Available: http://spennarmering.blogspot.com/2013/08/metermeganewton-mmn.html. [Accessed 2022].

[78] S. Smeplass, "Proporsjonering av lavkarbon. og lavernergi. betong," April 2017. [Online]. Available: https://www.standard.no/Global/PDF/Bygg,%20anlegg%20og%20eiendom/2017%20StMorg%20betong/5%20Sverre%20Smeplass%20Standard%20Morgen.pdf. [Accessed 2022].

[79] MERCELL, "Offentlige anskaffelser og krav til byggebransjen," [Online]. Available: https://anbudsbloggen.mercell.com/offentlige-anskaffelser-og-krav-til-byggebransjen. [Accessed 2022].

[80] J. Memmott, "Highway Bridges in the United States- an Overview," November 2012. [Online]. Available: https://www.bts.gov/archive/publications/special_reports_and_issue_briefs/special_report/2007_09_19/entire. [Accessed 2022].

[81] T. B. Mosland, "Erfaringer med utslippsfrie byggeplasser," October 2020. [Online]. Available: https://www.tekna.no/fag-og-nettverk/bygg-og-anlegg/byggbloggen/erfaringer-med-utslippsfrie-byggeplasser/. [Accessed 2022].

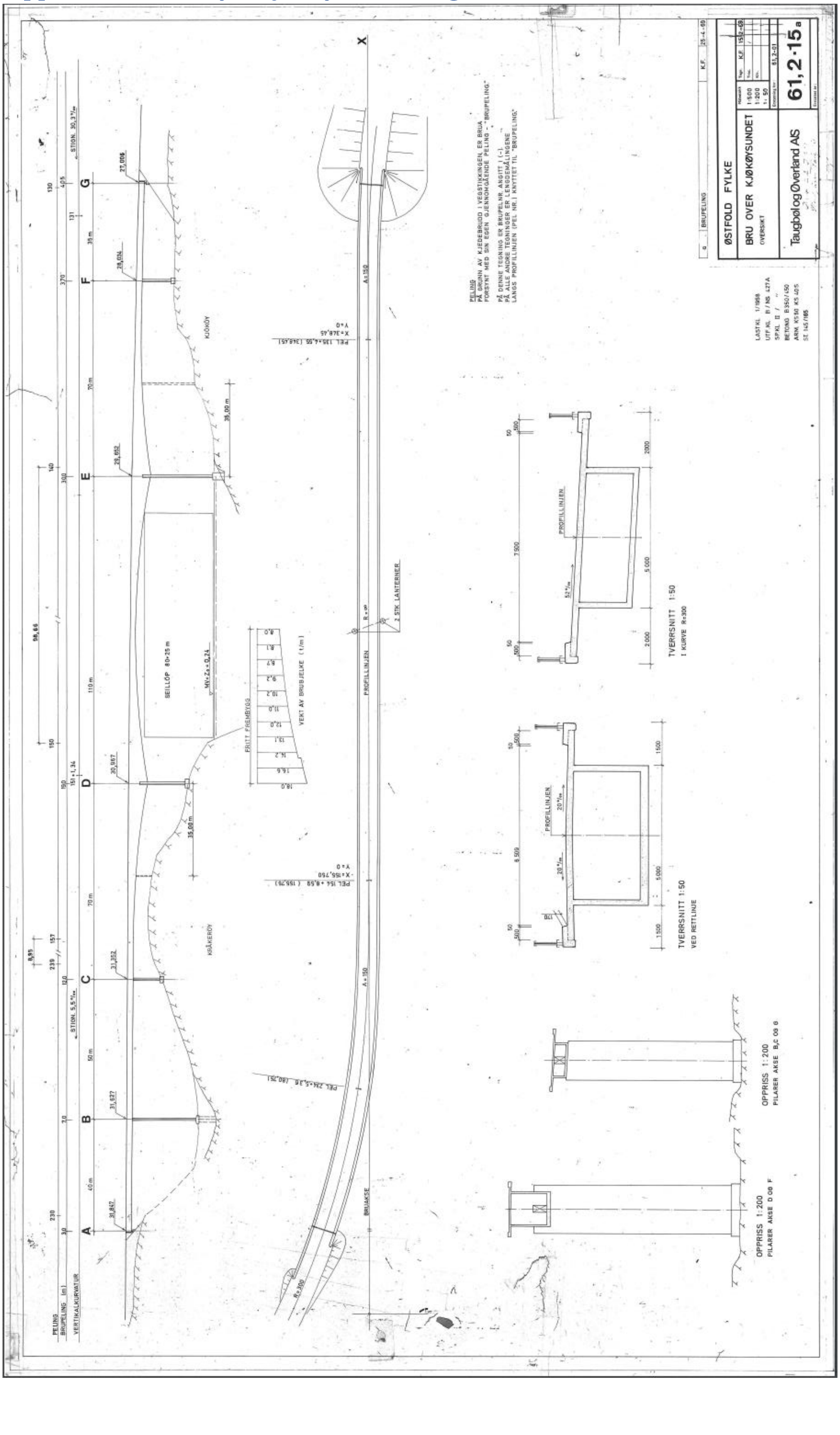
[82] EUROFER, "What is steel and how is steel made?," March 2020. [Online]. Available: https://www.eurofer.eu/about-steel/learn-about-steel/what-is-steel-and-how-is-steel-made/. [Accessed 2022].

[83] R. Sægrov and V. Meløysund, "Eurokoer," [Online]. Available: https://www.standard.no/fagomrader/bygg-anlegg-og-eiendom/eurokoder1/. [Accessed 2022].

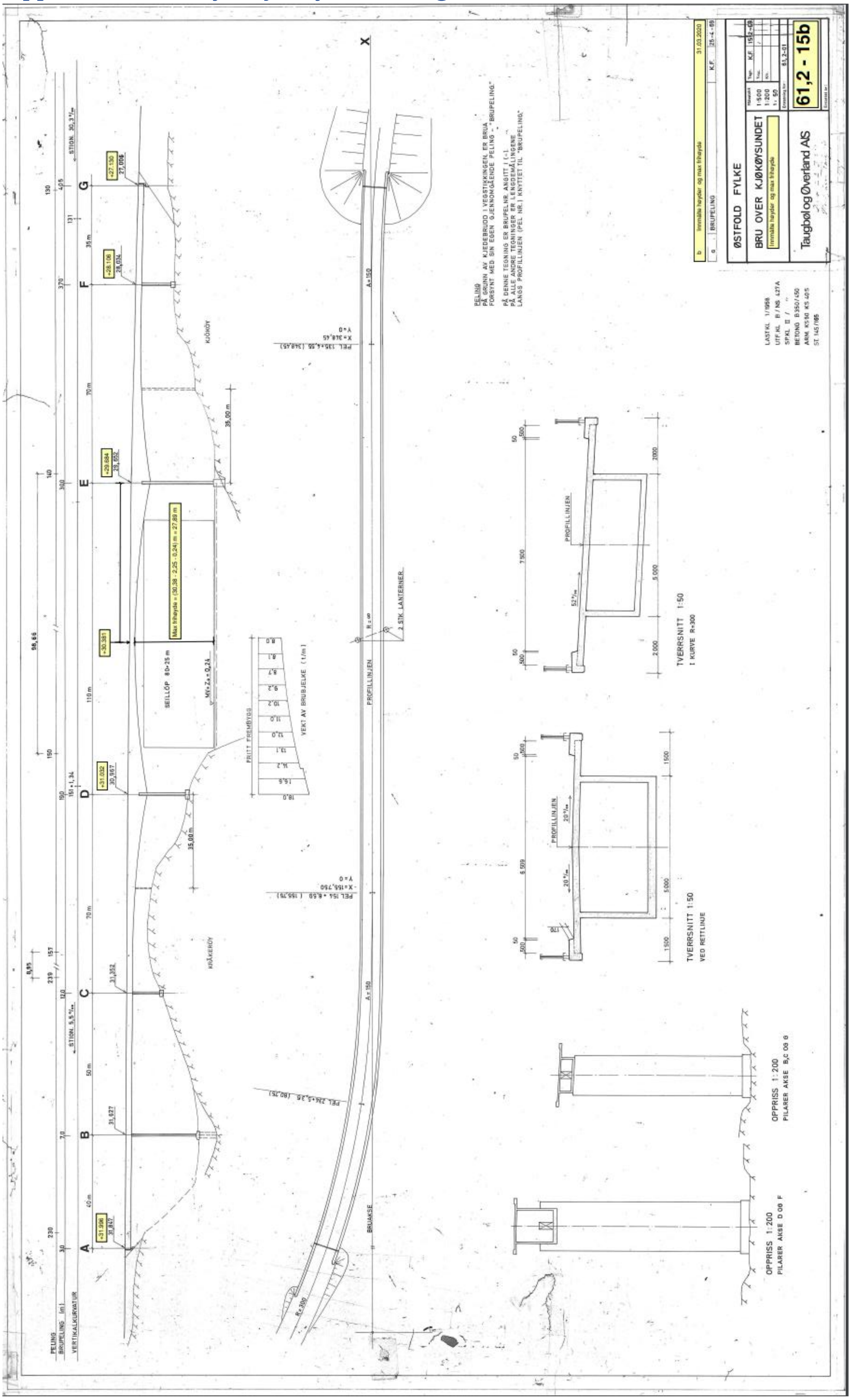
[84] NORCEM, "GOD BETONG ER BESTANDIG," [Online]. Available: https://www.norcem.no/sites/default/files/assets/document/godbetongerbestandig_web.pdf. [Accessed 2022].

Appendices

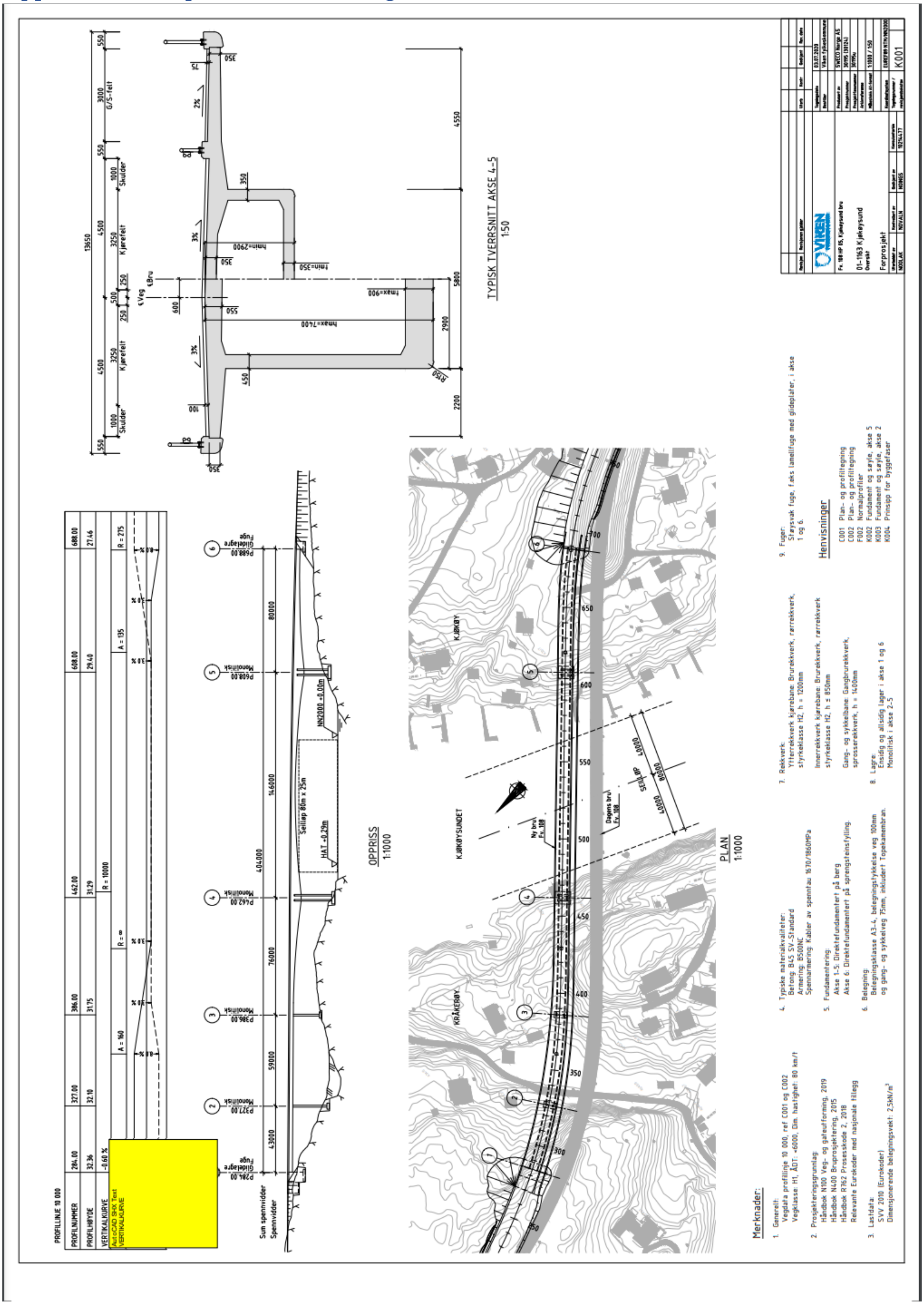
Appendix A: Todays Kjøkøysund bridge



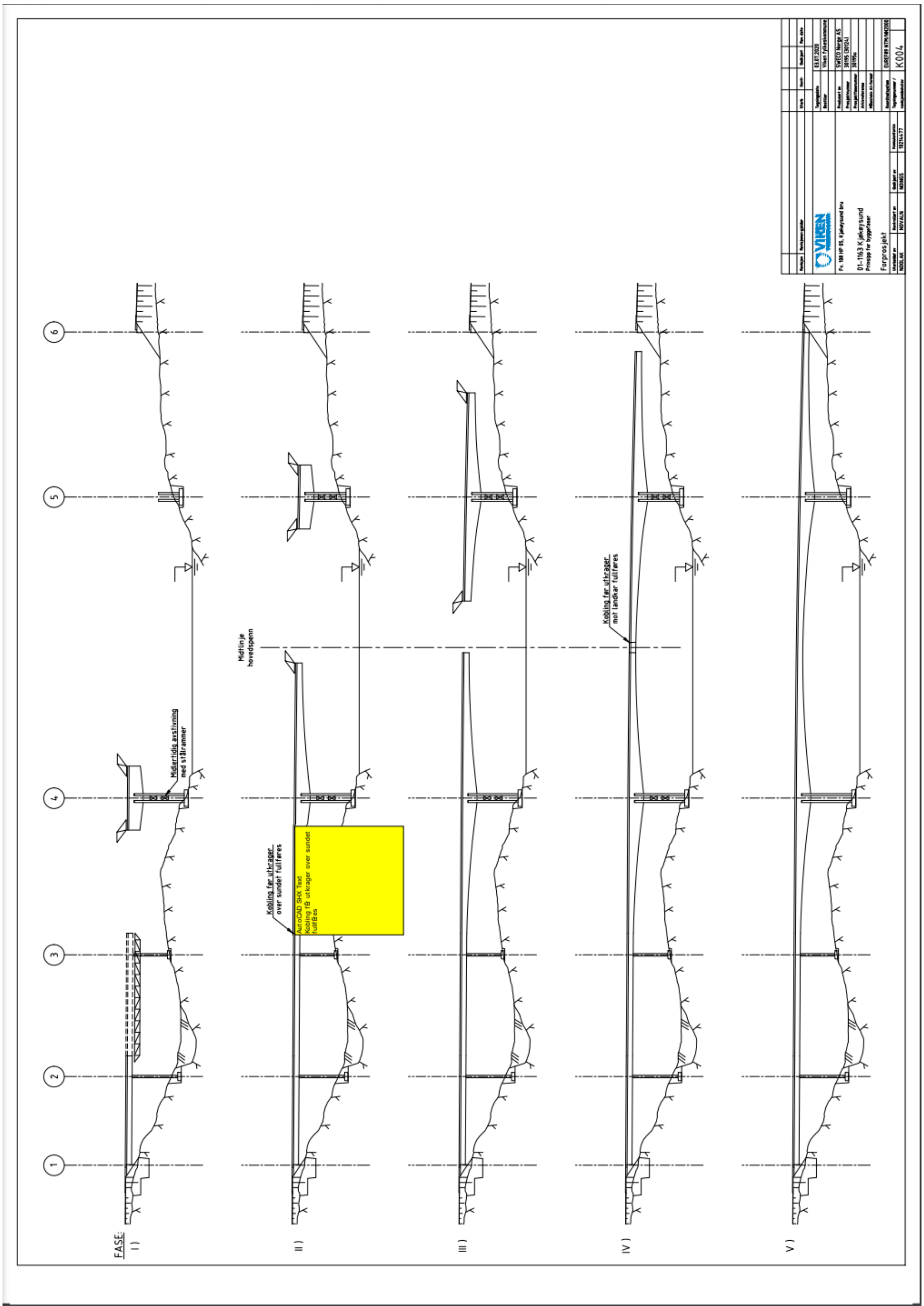
Appendix B: Todays Kjøkøysund bridge



Appendix C: Proposal for new bridge



Appendix D: Proposal for principle of construction phases



Appendix E: Simplified calculation done by Thorbjørn Valnes

Forenklet CO2-vurdering — 14.03.2022

Brutype: Betongkassebru sammenlignet med samvirkebru, to-felts kjørebru, føringsbredde typisk 10 m.

Spennvidder: Antar kontinuerlig bjelke/kassebru med typisk innerspenn ca. 50 m.

	Betongdekke blir omtrent det samme for begge brutypene. Sammenligner derfor kun bæresystemet under betongplata pr. m bru:		Mengder pr. m bru	CO2-ekv.		Tot. CO2
1.1	Betongkassebru, typisk tverrsnittareal for kassa uten dekke, betongvolum		3,7 m3/m	360 kgCO2/m3	1332 kg/m	2590 kg/m
	Armering i betongkassa,	200 kg/m3	740 kg/m	1,7 kgCO2/kg	1258 kg/m	
1.2	Samvirkebru, bæresystem to platebærere, samlet stålvekt typisk		2,3 tonn/m	1,7 kgCO2/kg		3910 kg/m

	Betongdekke blir omtrent det samme for begge brutypene. Sammenligner derfor kun bæresystemet under betongplata pr. m bru:			CO2-ekv.		Tot. CO2
2.1	Betongkassebru, typisk tverrsnittareal for kassa uten dekke, betongvolum		3,7 m3/m	290 kgCO2/m3	1073 kg/m	1961 kg/m
	Armering i betongkassa	200 kg/m3	740 kg/m	1,2 kgCO2/kg	888 kg/m	
2.2	Samvirkebru, bæresystem to platebærere, samlet stålvekt typisk		2,3 tonn/m	1,2 kgCO2/kg		2760 kg/m

	Betongdekke blir omtrent det samme for begge brutypene. Sammenligner derfor kun bæresystemet under betongplata pr. m bru:			CO2-ekv.		Tot. CO2
3.1	Betongkassebru, typisk tverrsnittareal for kassa uten dekke, betongvolum / m =		3,7 m3/m	290 kgCO2/m3	1073 kg/m	1591 kg/m
	Armering i betongkassa	200 kg/m3	740 kg/m	0,7 kgCO2/kg	518 kg/m	
3.2	Samvirkebru, bæresystem to platebærere, samlet stålvekt typisk		2,3 tonn/m	0,7 kgCO2/kg		1610 kg/m

Appendix F: EPD from Betong Øst (Low carbon A)

BETONG ØST

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage			Construction installation stage		User stage							End of life stage				Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling	Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X														

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00
ODP	kg CFC11 -eq	3,57E-06	1,29E-06	6,49E-07
POCP	kg C_2H_4-eq	3,09E-02	1,04E-03	7,21E-04
AP	kg SO_2 -eq	1,21E-01	2,13E-02	2,61E-02
EP	kg PO_4^{3-} -eq	1,27E-01	3,50E-03	5,61E-03
ADPM	kg Sb -eq	1,04E-04	1,31E-05	3,46E-06
ADPE	MJ	7,20E+02	1,02E+02	5,24E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix G: EPD from Betong Øst (Low carbon B)

BETONG ØST

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage			Construction installation stage		User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X														.	

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00
ODP	kg CFC11 -eq	3,57E-06	1,29E-06	6,49E-07
POCP	kg C_2H_4-eq	3,09E-02	1,04E-03	7,21E-04
AP	kg SO_2 -eq	1,21E-01	2,13E-02	2,61E-02
EP	kg PO_4^{3-} -eq	1,27E-01	3,50E-03	5,61E-03
ADPM	kg Sb -eq	1,04E-04	1,31E-05	3,46E-06
ADPE	MJ	7,20E+02	1,02E+02	5,24E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix H: EPD from NorBetong (Low carbon A)

NORBETONG
HEIDELBERGCEMENTGroup

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage			Construction installation stage		User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vann bruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	.	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,75E+02	1,66E+01	4,76E+00	1,95E+00
ODP	kg CFC11 -eq	3,31E-06	3,18E-06	8,37E-07	3,68E-07
POCP	kg C_2H_4-eq	2,53E-02	2,93E-03	6,57E-04	3,45E-04
AP	kg SO_2 -eq	1,22E-01	8,07E-02	1,28E-02	6,85E-03
EP	kg PO_4^{3-} -eq	1,02E-01	1,56E-02	1,62E-03	1,43E-03
ADPM	kg Sb -eq	9,73E-05	2,53E-05	5,60E-06	4,30E-06
ADPE	MJ	6,23E+02	2,52E+02	6,53E+01	2,97E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix I: EPD from NorBetong (Low carbon B)

NORBETONG
HEIDELBERGCEMENT Group

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	.	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,31E+02	8,27E+00	4,76E+00	2,03E+00
ODP	kg CFC11 -eq	3,54E-06	1,68E-06	8,37E-07	3,84E-07
POCP	kg C_2H_4-eq	3,08E-02	1,34E-03	6,57E-04	3,60E-04
AP	kg SO_2 -eq	1,18E-01	2,63E-02	1,28E-02	7,15E-03
EP	kg PO_4^{3-} -eq	1,27E-01	4,18E-03	1,62E-03	1,49E-03
ADPM	kg Sb -eq	1,02E-04	1,76E-05	5,60E-06	4,49E-06
ADPE	MJ	7,10E+02	1,34E+02	6,53E+01	3,10E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix J: EPD from Vestfold Betong (Low carbon A)

VESTFOLD BETONG

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	.	MND

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,88E+02	9,06E+00	4,51E+00	3,06E+00
ODP	kg CFC11 -eq	4,00E-06	1,86E-06	7,99E-07	5,79E-07
POCP	kg C_2H_4-eq	1,38E-02	1,42E-03	9,08E-04	5,43E-04
AP	kg SO_2 -eq	3,47E-01	2,34E-02	3,35E-02	1,08E-02
EP	kg PO_4^{3-} -eq	7,46E-02	3,23E-03	7,23E-03	2,24E-03
ADPM	kg Sb -eq	1,17E-04	2,16E-05	4,70E-06	6,77E-06
ADPE	MJ	5,93E+02	1,49E+02	6,45E+01	4,68E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix K: EPD from Vestfold Betong (Low carbon B)

VESTFOLD BETONG

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage				Construction installation stage	User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	.	MND

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,04E+02	9,08E+00	4,51E+00	3,06E+00
ODP	kg CFC11 -eq	4,23E-06	1,87E-06	7,99E-07	5,79E-07
POCP	kg C_2H_4-eq	1,45E-02	1,42E-03	9,08E-04	5,43E-04
AP	kg SO_2 -eq	3,70E-01	2,34E-02	3,35E-02	1,08E-02
EP	kg PO_4^{3-} -eq	7,90E-02	3,23E-03	7,23E-03	2,24E-03
ADPM	kg Sb -eq	1,20E-04	2,16E-05	4,70E-06	6,77E-06
ADPE	MJ	6,25E+02	1,49E+02	6,45E+01	4,68E+01

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

Appendix L: Excel calculations for concrete

Low carbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,75E+02	1,66E+01	4,76E+00	1,95E+00

Low carbon A	GWP	
A1	175	kgCO2/m^3
A2	16,6	kgCO2/m^3
A3	4,76	kgCO2/m^3
Total	196,36	kgCO2/m^3

Volume of Kjøkøysund bridge box								
Top flange	0,483333333	m	Web width	0,416666667	m	Bottom flange width	2,9	m
Bridge width	13,65	m	Web height	5,416666667	m	Bottom bridge thickness	0,716666667	m
Bridge length	1	m	Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3	V=	4,513888889	m^3	V=	2,078333333	m^3
Total Volume=	13,18972222							

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	196,36	kgCO2/m^3	**2589,933856**	kg/m

B35 M45

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,04E+02	9,08E+00	4,51E+00	3,06E+00

	GWP	
A1	204	kgCO2/m^3
A2	9,08	kgCO2/m^3
A3	4,51	kgCO2/m^3
Total	217,59	kgCO2/m^3

Volume of Kjøkøysund bridge box								
Top flange	0,48	m	Web width	0,42	m	Bottom flange width	2,9	m
Bridge width	13,65	m	Web height	5,42	m	Bottom bridge thickness	0,72	m
Bridge length	1	m	Bridge length	1	m	Bridge length	1	m
V=	6,60	m^3	V=	4,51	m^3	V=	2,08	m^3
Total Volume=	13,19	m^3						

Amount pr.m bridge		CO2-ekv		Total CO2
13,19	m^3/m	217,59	kgCO2/m^3	**2869,95 kg/m**

Lavkarbon B og Lavkarbon A

Lavkarbon B

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,04E+02	9,08E+00	4,51E+00	3,06E+00

Lavkarbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,88E+02	9,06E+00	4,51E+00	3,06E+00

Lavkarbon B	GWP	
A1	204	kgCO2/m^3
A2	9,08	kgCO2/m^3
A3	4,51	kgCO2/m^3
Total	217,59	kgCO2/m^3

Lavkarbon A	GWP	
A1	188	kgCO2/m^3
A2	9,06	kgCO2/m^3
A3	4,51	kgCO2/m^3
Total	201,57	kgCO2/m^3

B

Volume of Kjøkøysund bridge box				A					
Top flange	0,48333333	m		Web width	0,416666667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,416666667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,513888889	m^3	V=	2,078333	m^3
Total Volume=	13,1897222								

B

Amount pr.m bridge		CO2-ekv		Total CO2	
B					
6,5975	m^3/m	217,59	kgCO2/m^3	1435,550025	kg/m
A					
6,59222	m^3/m	201,57	kgCO2/m^3	1328,794233	kg/m
			Total for Both	**2764,344258**	kg/m

Low carbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,88E+02	9,06E+00	4,51E+00	3,06E+00

Low carbon A	GWP	
A1	188	kgCO2/m^3
A2	9,06	kgCO2/m^3
A3	4,51	kgCO2/m^3
Total	201,57	kgCO2/m^3

Volume of Kjøkøysund bridge box									
Top flange	0,483333	m		Web width	0,416667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,416667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,513889	m^3	V=	2,078333	m^3
Total Volume=	13,18972								

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	201,57	kgCO2/m^3	**2658,652308**	kg/m

31826,79972

B35 M45

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00

	GWP	
A1	231	kgCO2/m^3
A2	6,36	kgCO2/m^3
A3	3,58	kgCO2/m^3
Total	240,94	kgCO2/m^3

Volume of Kjøkøysund bridge box									
Top flange	0,483333	m		Web width	0,4166667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,4166667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,5138889	m^3	V=	2,078333	m^3
Total Volume=	13,18972	m^3							

Amount pr.m bridge		CO2-ekv		Total CO2	
13,19	m^3/m	240,94	kgCO2/m^3	3177,93	kg/m

Lavkarbon B og Lavkarbon A

Lavkarbon B

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	2,31E+02	6,36E+00	3,58E+00

Lavkarbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	1,96E+02	4,31E+00	3,17E+00

Lavkarbon B	GWP	
A1	231	kgCO2/m^3
A2	6,36	kgCO2/m^3
A3	3,58	kgCO2/m^3
Total	240,94	kgCO2/m^3

Lavkarbon A	GWP	
A1	196	kgCO2/m^3
A2	4,31	kgCO2/m^3
A3	3,17	kgCO2/m^3
Total	203,48	kgCO2/m^3

Volume of Kjøkøysund bridge box									
Top flange	0,483333333	m		Web width	0,416667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,416667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,513889	m^3	V=	2,078333	m^3
Total Volume=	13,18972222								
B									
Amount pr.m bridge		CO2-ekv		Total CO2					
B									
6,5975	m^3/m	240,94	kgCO2/m^3	1589,60165	kg/m				
A									
6,5922		203,48	kgCO2/m^3	1341,385378	kg/m				
			Total for both	**2930,987028**	kg/m				

Low carbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3
GWP	kg CO_2 -eq	1,96E+02	4,31E+00	3,17E+00

Low carbon A	GWP	
A1	196	kgCO2/m^3
A2	4,31	kgCO2/m^3
A3	3,17	kgCO2/m^3
Total	203,48	kgCO2/m^3

Volume of Kjøkøysund bridge box									
Top flange	0,483333	m		Web width	0,416667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,416667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,513889	m^3	V=	2,078333	m^3
Total Volume=	13,18972								

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	203,48	kgCO2/m^3	**2683,844678**	kg/m

B35 M45

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,31E+02	8,27E+00	4,76E+00	2,03E+00

	GWP	
A1	231	kgCO2/m^3
A2	8,27	kgCO2/m^3
A3	4,76	kgCO2/m^3
Total	244,03	kgCO2/m^3

Volume of Kjøkøysund bridge box									
Top flange	0,483333333	m		Web width	0,4167	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,4167	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,5139	m^3	V=	2,078333	m^3
Total Volume=	13,18972222	m^3							

Amount pr.m bridge		CO2-ekv		Total CO2	
13,18972222	m^3/m	244,03	kgCO2/m^3	3218,687914	kg/m

Lavkarbon B og Lavkarbon A

Lavkarbon B

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	2,31E+02	8,27E+00	4,76E+00	2,03E+00

Lavkarbon A

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4
GWP	kg CO_2 -eq	1,75E+02	1,66E+01	4,76E+00	1,95E+00

Lavkarbon B	GWP	
A1	231	kgCO2/m^3
A2	8,27	kgCO2/m^3
A3	4,76	kgCO2/m^3
Total	244,03	kgCO2/m^3

Lavkarbon A	GWP	
A1	175	kgCO2/m^3
A2	16,6	kgCO2/m^3
A3	4,76	kgCO2/m^3
Total	196,36	kgCO2/m^3

B									
Volume of Kjøkøysund bridge box				A					
Top flange	0,483333	m		Web width	0,416667	m	Bottom flange width	2,9	m
Bridge width	13,65	m		Web height	5,416667	m	Bottom bridge thickness	0,716667	m
Bridge length	1	m		Bridge length	1	m	Bridge length	1	m
V=	6,5975	m^3		V=	4,513889	m^3	V=	2,078333	m^3
Total Volume=	13,18972								

B					
Amount pr.m bridge		CO2-ekv		Total CO2	
B					
6,5975	m^3/m	244,03	kgCO2/m^3	1609,987925	kg/m
A					
6,5922		196,36	kgCO2/m^3	1294,448756	kg/m
			Total for Both	**2904,436681**	kg/m

Appendix M: Excel calculations for steel

Beregning av stålmengde for stålkasse alternativ for kjøkøysund bru

Vanlig stål									
Tykkelse stål		25	mm						
Bredde nedre flens		7000	mm						
Høyde steg		5000	mm						
TVERSNITT									
	Tykkelse	Bredde	Areal		Lengde			Volum	
Flens	25	7000	175000	mm2	110000	mm		1,93E+10	mm3
Steg	25	5500	137500	mm2	100000	mm		1,38E+10	mm3
Steg	25	5500	137500	mm2	100000	mm		1,38E+10	mm3
							Totalt	4,68E+10	mm3
								46,7	m3
					Densitet stål		7,85	t/m3	
							Weight	366,595	ton
							Margin	20 %	
							Totalt	439,914	ton
MALING									
	Lengde	Bredde	Areal		Areal m2				
Flens	110000	7000	7,7E+08	mm2	770	m2			
Steg	110000	5500	6,05E+08	mm2	605	m2			
Steg	110000	5500	6,05E+08	mm2	605	m2			
				Totalt	1980	m2			

Høyfast stål									
Tykkelse stål		15	mm						
Bredde nedre flens		7000	mm						
Høyde steg		5000	mm						
TVERSNITT									
	Tykkelse	Bredde	Areal		Lengde			Volum	
Flens	15	7000	105000	mm2	110000	mm		1,16E+10	mm3
Steg	15	5500	82500	mm2	100000	mm		8,25E+09	mm3
Steg	15	5500	82500	mm2	100000	mm		8,25E+09	mm3
			270000	mm2			Totalt	2,81E+10	mm3
								28,05	m3
					Densitet stål		7,85	t/m3	
							Weight	220,1925	ton
							Margin	20 %	
							Totalt	264,231	ton
MALING									
	Lengde	Bredde	Areal		Areal m2				
Flens	110000	7000	7,7E+08	mm2	770	m2			
Steg	110000	5500	6,05E+08	mm2	605	m2			
Steg	110000	5500	6,05E+08	mm2	605	m2			
				Totalt	1980	m2			

Beregning av oppspenningskabel mengde for Kjøkøysund bru

De største utfording de fleste har i spennarmering er møte med meterMegaNewton (mMN).
Selve formelen er da veldig komplisert den sier da:

$$f_y \cdot \sum_{i-1}^{n} L_i \cdot A_{si}$$

Men den er ikke så komplisert som den ser ut.
- fy er normalt fp0,1k som er normalt 1640MPa, enkelte bruker også fp0,2k grensen som er 1670MPa. Dette kan variere fra konsulent til konsulent.
- Den store SUM Li er i meter og måles fra anker til anker, dvs. hvis lengden er 60 m og der er 19 liner (tau) i kabelen ganges disse: 60 x 19 = 1140 meter med tau (også kaldt stål i spennarmeringsbranchen).
- Asi er tversarealet av trådene, i Norge brukes kun to typer 0,60" eller 0,62" (140mm^2 eller 150mm^2), typisk 0,60" (140mm^2).

Der er mange typer spennstål med diverse tverssnitt. I dette tilfelle fås mMN til:

(1,640x60x19x140)/1000=262 mMN

Hvis dere får et lidt andeledes tall enn hva byggherre har angitt, så er det at kommentere med egne kalkulasjoner (det er veldig ofte at BH kalkulerer feil).

Håper dette gir litt forståelse om meterMegaNewton (mMN).Om dere har spørsmål så er det bare at kommentere.

Fra rapport	47200	mMN
Hovedspenn	23 600	mMN
Fy	1,64	fy
Asi	150	mm2
Li	110	m
tau	25	
sum	676,5	mMN
antall spennkabel	34,88544	stk
Areal per liss	150	mm2
Antall liss per kabel	25	stk
Antall kabel	35	stk
Lengde per kabel	110000	mm
volum	1,44E+10	mm3
	14,4	m3